WL-TR-92-8014

INCREASING MACHINE TOOL PRODUCTIVITY WITH HIGH PRESSURE CRYOGENIC COOLANT FLOW

Institute of Advanced Manufacturing Sciences, Inc. (IAMS)
1111 Edison Drive
Cincinnati, Ohio 45216

May 1992

Final Report for Period August 1989 - December 1991

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REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1992	FTR - August 1989 - December 1991

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Increasing Machine Tool Productivity with High Pressure Cryogenic Coolant Flow	C: F33615-89-C-5730 PE: 78011F PR: 3095 TA: 06 WU: 21
6. AUTHOR(S)	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Institute of Advanced Manufacturing Sciences, Inc. 1111 Edison Drive Cincinnati, Ohio 45216	Report No. APQ-139

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REP NUMBER
Siamack Mazdiyasni, WL/MTPM, 513/255-2413 Manufacturing Technology Directorate Wright Laboratories Wright Patterson AFB, OH 45433-6533	WL-TR-92-8014

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for Public Release; Distribution is Unlimited	

13. ABSTRACT

The Institute of Advanced Manufacturing Sciences, Inc. (IAMS) in Cincinnati has conducted a program to evaluate the Flojet® high pressure cryogenic coolant system on a number of common and difficult-to-machine materials and to analyze the economic benefits. This research contract was awarded under the Air Force's Machine Tool Products and Processes Program Research and Development Announcement (PRDA). The program included a continuing forum with interested industrial representatives to disseminate information about the system and to identify questions and concerns from potential users that might be addressed in testing.

The Flojet system, a product of PXI, Incorporated, has the potential to significantly improve operations in the metal-cutting industry. It is a coolant delivery system that produced a very high pressure stream of cooland and a parallel stream of CO_2 which are aimed at the cutting zone. It is designed to provide improved chip-breaking, longer tool life, reduced cutting forces, and improved workpiece quality. The inventor and several other parties formed PXI, Inc. to market and continue development of the system which presently has only a small installed base of industrial users.

14. SUBJECT TERMS	15. NUMBER OF PAGES
machining, coolant - high pressure, *flojet*, chip control	216
	16. PRICE CODE NA

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASS OF THIS PAGE.	19. SECURITY CLASS OF ABSTRACT	20. LIMITATION ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z239-18
298-102

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PREFACE

This Final Report presents the results of a laboratory evaluation of the ***flojet*** system performed by the Institute of Advanced Manufacturing Sciences, Inc. under Air Force Contract F33615-89-C-5730. The contract's objective is to provide independent data on the performance of the ***flojet*** system. As contractor, the Institute is serving as an independent testing laboratory with no commercial interest in the ***flojet*** system or with PXI, Inc. the owners of the ***flojet*** system. As an independent laboratory, the Institute evaluated the ***flojet*** system under documented machining conditions representative of common industrial practice. Neither the Institute, the U.S. Air Force, nor the U.S. Government make any claims as to the suitability of the ***flojet*** system for specific industrial applications. The data presented in this Final Report is intended to assist individuals and firms with their evaluation of the ***flojet*** system for their specific applications. Questions as to the methods used to test the ***flojet*** system, the data, the data analysis, or its presentation can be directed to the Air Force project manager or the Institute.

INCREASING MACHINE TOOL PRODUCTIVITY WITH HIGH-PRESSURE CRYOGENIC COOLANT FLOW

February 7, 1992

SCOPE

The scope of the program is to investigate the performance of a new machining technology described as a "very high-pressure cryogenic stream" coolant system. A stream of pressurized cutting fluid (up to 6000 psi) and a parallel stream of CO_2 are directed at the zone where the chip is forming over the rake face of the cutting tool. It is a patented system marketed as ***flojet®*** by Productivity Experts, Inc. (PXI) of Cincinnati, Ohio. The current program is limited to O.D. turning of a number of materials although the ***flojet*** system can be adapted to a variety of machining processes. The project is sponsored by the Manufacturing Technology Directorate of the United States Air Force and performed by the Institute of Advanced Manufacturing Sciences.

EXECUTIVE SUMMARY

The ***flojet*** system is shown to be an effective device for providing chip control and in some cases significant increases in tool life. However, no significant effects on surface finish, cutting forces, or power were noted for the tested materials over a range of machining parameters. Turning off the CO_2 stream did not influence the performance of the ***flojet*** process for any of the tested conditions. A rigorous economic analysis indicates that ***flojet*** may be economically justified where its use allows higher speeds and/or longer tool life, or where otherwise intractable chip control problems are limiting productivity or preventing unattended operation.

The responses of potential industrial users throughout the program, and particularly at the first industry briefing, indicate that the most attractive benefit of ***flojet*** is the potential for comprehensive chip control. The inability to produce small broken chips for many combinations of workpiece materials and operating conditions is a major concern of the machining industry. Long stringy chips and "birds nests" cause damage to the tool and workpiece, are a hazard to the operator, cause increased downtime and expense, and may prevent an otherwise feasible implementation of unattended machining. Chip control testing during this program included light and heavy cuts in aluminum, steel, stainless steel, titanium, inconel, and M-50 (R_c 61) bearing

steel. In the flood coolant control group, many of the test conditions produced long or difficult chips despite the use of mechanical chip breakers. Under almost all test conditions the use of ***flojet*** resulted in broken, manageable chips.

Tool life tests were performed for all of the same materials except aluminum. Carbide tools were used for all materials except the M-50. In addition, whisker reinforced ceramic and CBN tools were used for the inconel and M-50. Use of the ***flojet*** system produced approximately double the tool life compared to flood fluid application for the carbide tools. Conversely, for a given tool life ***flojet*** permits more aggressive operating parameters and increased productivity. Use of ***flojet*** did not have a significant effect on tool life when using CBN inserts or when using the whisker reinforced ceramic inserts on the hard M-50. When the ceramic inserts were used to machine the inconel, ***flojet*** produced a significant <u>decrease</u> in tool life.

Testing was performed to determine if use of the ***flojet*** system improved surface finish, reduced cutting forces, lowered horsepower requirements, or had an affect on the surface metallurgy of the workpiece material. The same group of workpiece materials was used as in the previous tests. In each case, there was no significant difference between ***flojet*** and flood fluid application.

The ***flojet*** system can be operated with the CO_2 stream turned off, using only the high-pressure stream of cutting fluid. No significant performance differences were noted during any of the tests conducted comparing ***flojet*** with the CO_2 turned on, and ***flojet*** with the CO_2 turned off. It should also be noted that omitting the CO_2 has only minor effect on the results of the economic analysis.

An analysis of each of the workpiece/tool combinations indicates that economic justification of the ***flojet*** system depends on significant increases in tool life and higher speeds which result in higher productivity. For the rates and assumptions used in the analysis, this was the case for most of the tests using carbide inserts. The less tangible benefits of increased safety and improved process consistency due to chip control may also justify ***flojet*** implementation. The economic analysis indicated a clear and substantial benefit to adding an unattended production shift. If this is feasible except for the problem of chip control, then ***flojet*** is easily justified (except with the ceramic tooling where increased cost per part may offset productivity gains). The use or omission of CO_2 is insignificant in the economic analysis.

PROGRAM GOALS

This program is designed to validate the performance of ***flojet***, to quantify the potential benefits to industrial users, and to provide the information needed to make decisions on implementing this emerging technology.

The specific goals of the program are as follows:

- Improve U.S. industrial competitiveness through implementation support of innovative machine tool technology
- Evaluate the technical performance of ***flojet*** over a range of workpiece materials and operating conditions
- Perform an economic analysis to determine the impact of implementing the ***flojet*** system on cost per part and productivity
- Transfer technical information about ***flojet*** to industry and identify industry needs and concerns with respect to the potential benefits of the technology
- Encourage and assist technology innovation by small entrepreneurial businesses

A number of productivity and quality improvements have been attributed to use of the ***flojet*** system. If validated, they could have significant impact on the competitiveness of a machining business. Each of the following claims is specifically addressed in the program through controlled laboratory testing:

- Chip Control – producing small broken chips
- Increased Tool Life
- Increased Productivity – allowing more aggressive operating parameters and reducing downtime due to chip problems
- Improved Surface Finish
- Reduced Cutting Forces and Horsepower Requirement

PROGRAM APPROACH

The three main tasks of the program are to review the currently available techniques for chip control, to interface with industry to identify needs and expose the technology, and to test the performance of the ***flojet*** system.

State-of-the-Art Review

At the beginning of the program, a literature search was conducted to identify current and emerging methods of chip control. The results of this study and the associated bibliography were presented at the first industry briefing and are included as an appendix to this report.

Technology Transfer

A major goal of this program is to inform potential industrial users about a new machining technology, to provide an assessment of its potential for their judgement, and to identify their needs and concerns with respect to the potential benefits of the technology. To this end, the program includes interim and final industry briefings and an industrial advisory board, as well as this Final Report.

Performance Evaluation

The performance of the ***flojet*** system was compared to that of flood coolant application in laboratory testing on a variety of workpiece materials. Tests included chip-breaking performance, tool life, surface finish, cutting force, and power. An analysis was also performed comparing the economics of ***flojet*** and flood coolant for each of the tested materials.

CHIP CONTROL ISSUES AND METHODS

Chip control has been identified by the industrial participants in this program as a major concern in machining operations. Long tangled chips have long posed a number of problems in machining processes including damage to the tool and workpiece, operator safety concerns, and disposal of large volumes of low-density waste (often addressed by adding a compaction system).

Two more recent factors have contributed to the urgency of addressing this problem. The first is the wider use of new, tougher materials which do not readily form manageable chips. The second is the move toward unattended machining for improved productivity and quality (process

consistency). These processes demand short broken chips that are consistently ejected from the cutting zone, can be reliably handled by chip conveyor systems, and can be stored and transported in a minimum volume.

Chip Control Methods

A number of approaches have been applied to the problem of producing manageable chips, with varying degrees of success. These include:

- Altering the material condition or process parameters

- Clamp-on chip breakers

- Chip-breaking insert geometries

- Fluid application at various pressures

"high"	(~100 psi)
"very high"	(~1 - 10 ksi) including ***flojet***
"ultra-high"	(~10+ ksi) including Water Jet Assisted Machining (JAM)

- Applied vibration

- Relaxation or interrupted feed

A literature survey on chip control was performed in the early phases of the program to prepare a state-of-the-art report which was delivered at the first Industry Briefing. The report provides additional detail on the approaches listed above, as well as a bibliography of literature on the subject. It is included here as APPENDIX A.

One technology that has emerged since the preparation of that study is the Water Jet Assisted Machining (JAM) work at The Advanced Manufacturing Center at Cleveland State University by Dr. Schoenig, Dr. Frater, and Dr. Lindeke. This method applies a 40 ksi coolant stream to the tool-chip contact area through a hole in the rake face of the insert. In exploratory experiments it has been shown to break chips and increase tool life in difficult-to-machine materials. JAM is not currently a commercially available system.

DESCRIPTION OF THE TEST SYSTEM

The *flojet* System

The ***flojet*** system tested during this program delivers parallel streams of pressurized coolant and CO_2 to a point on the rake face of the insert just behind the cutting edge. During cutting, the stream may impinge on the back side of the chip. The nozzle assembly can be aimed within a narrow range to compensate for differences in toolholders or depth of cut. Testing was performed on a Cincinnati Milacron Cinturn 10CC NC Turning Center. A single turret position was modified to accept the ***flojet*** nozzle assembly.

The fluid pressure is adjustable; for consistency the test system was adjusted to 5,500 psi which was sufficient to produce broken chips in all of the test materials. In general, lower fluid pressures are sufficient for easier-to-machine materials. Standard water-based cutting fluids are used.

The CO_2 is metered to the nozzle through a delivery hose by a valve mounted near the supply tank. The valve is controlled by a PLC through which the duty cycle of the valve may be adjusted. In operation, the valve is open for a short period which charges the delivery line, and then the valve is closed while the line bleeds down. The cycle is adjusted to produce an uninterrupted stream of CO_2 from the nozzle. The test system was set at one-half second ON, and 12 seconds OFF.

A schematic of the system is shown in Figure 1. Physically, it is comprised of three subsystems. The Power Pack is placed near the machine and contains low- and high-pressure pumps, a filtration system, and the controller. The test unit contains a 50-horsepower pump, which would usually be specified to service two machine tools while a 30-horsepower unit is sufficient for a single operation. A small operator control box is tethered to the Power Pack. The second subsystem is the gas supply system consisting of a siphon supply tank (or dewar) and the control valve. The inducer/nozzle assembly mounts to the tool block and is customized by the manufacturer for the specific machine. The nozzle itself is separately replaceable.

Because of the high-pressure fluid stream, fluid retention and mist collection are significant issues. A mist collector is a standard component of the system as supplied by the manufacturer. The machine tool must also be well sealed both internally (to prevent shorting of electrical components) and externally (to prevent fluid loss).

The consumables in the ***flojet*** system are the CO_2 gas, filters in the Power Pack and mist

collection system, and cutting fluid. Fluid consumption on the test bed was somewhat higher than for normal flood operation, though this will depend significantly on the degree to which the machine is sealed and the effectiveness of the mist collector. Operating hours on the test bed were not sufficient to judge the average filter replacement schedule.

It should be noted that there have been several previous generations of this system, including those produced under the **Ultiflow** name, which differ in significant detail from the current version. Some have a nozzle assembly in which the fluid and gas are mixed in the nozzle and exit through a single orifice. Although design improvements continue to be made, the test system fairly represents the performance of the current commercially available system at the date of this report.

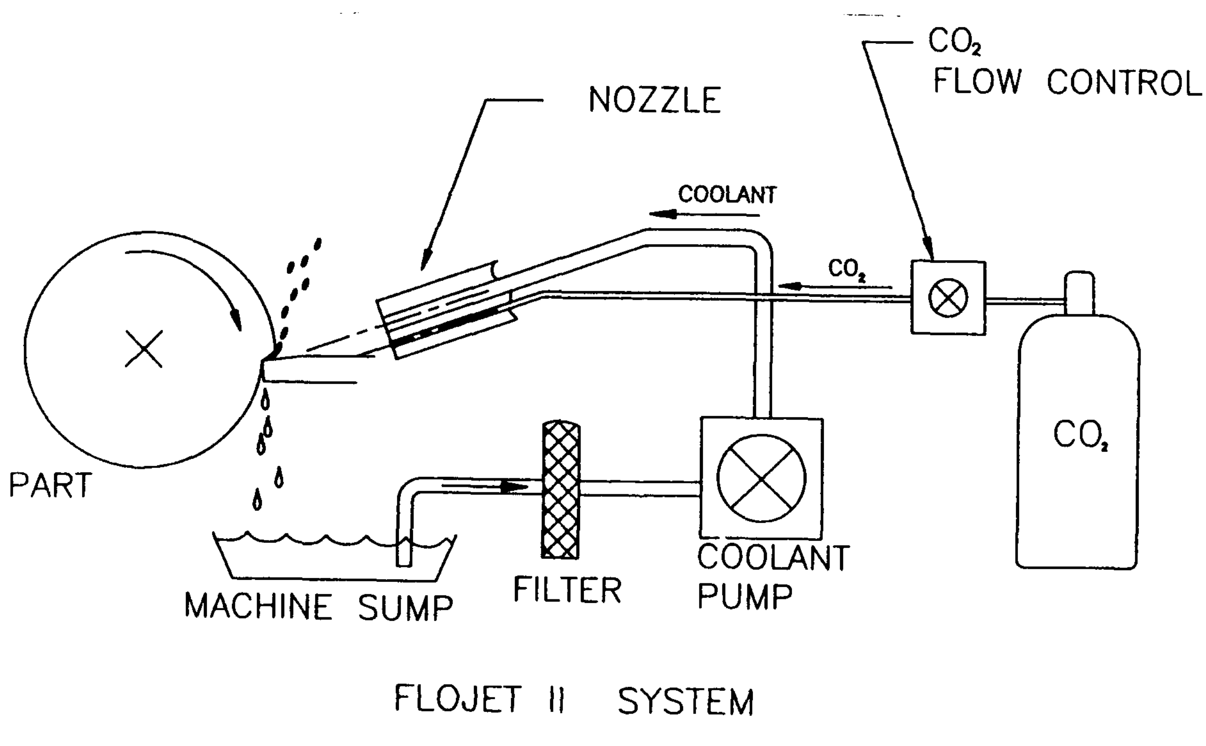


Figure 1 - ***flojet*** System Diagram

The Test Configuration

- CUTTING FLUID: Trim Sol (Master Chemical) 20:1
- ***flojet*** NOZZLE ORIFICE DIAMETER*: 0.052 inch
- ***flojet*** FLUID PRESSURE SETTING*: 5,500 psi
- ***flojet*** FLUID FLOW RATE (MEASURED): 5-6 gallons/minute
- FLOOD COOLANT FLOW RATE (MEASURED): 3 gallons/minute
- ***flojet*** CO_2 CYCLE SETTING*: 1/2 second ON, 12 seconds OFF
- ***flojet*** CO_2 CONSUMPTION RATE (MEASURED): 11.5 pounds/cutting hour

  * For a ***flojet*** installation with a narrow range of workpiece materials, these parameters would be optimized at installation. For some applications, the required pressure and flow rates might be significantly lower.

DESCRIPTION OF THE PERFORMANCE TESTS

Test Materials

Nine combinations of workpiece and tool materials were tested for chip control, forces, and surface finish. Tool life testing was performed on all combinations except the aluminum, because the selected alloy does not wear carbide tools at a significant rate. The test matrix is summarized in Table 1.

Table 1 - Workpiece/Tool Material Matrix

Workpiece Material	Hardness	Tool Material
7075-T6	140-160 Bhn	Carbide
4340 Steel	320-360 Bhn	Carbide
17-4 PH Stainless Steel	320-360 Bhn	Carbide
Ti-6AL-4V Titanium	320-360 Bhn	Carbide
Inconel 718	40-42 R_c	Carbide
Inconel 718	40-42 R_c	Whisker Reinforced Ceramic
Inconel 718	40-42 R_c	CBN
M-50 Steel	61 R_c	Whisker Reinforced Ceramic
M-50 Steel	61 R_c	CBN

Tooling

All test operations were O.D. turning using CNM_543 - 80 diamond inserts. Inserts for the chip-breaking studies were selected by polling several leading insert suppliers to determine their recommended product for each of the test materials. The selections were very consistent from vendor to vendor with respect to insert geometry and material grade. Flat-top insert styles were used for all ***flojet*** tests; the recommended chip-breaker designs were used for flood coolant tests. If a chip-breaker design was not available for a particular insert grade clamp type chip breakers were used where required during flood coolant tests.

All life and force tests were performed with flat-top inserts to improve the consistency of wear measurement. Additionally, CNM_432 inserts were selected where available to provide a longer flank wear zone (due to the smaller nose radius). Clamp-type chip breakers were used as needed with flood coolant to facilitate testing. All carbide inserts in the wear tests were uncoated.

A summary of the test tooling is provided below in Table 2.

Table 2 - Tools

WORKPIECE MATERIAL	TEST/TOOL (STYLE, GRADE)		
	Chip Control – Flood	Chip Control – flojet	Life
Aluminum	CNGP543K, K313	CNMA543, K313	-----
4340	CNMG543, KC850	CNMA543, KC850	CNMA-432, 415
17-4	CNMG543, KC950	CNMA543, KC950	CNMA-432, 415
Titanium	CNGP543K, K313	CNMA543, K313	CNMA-432, H13A
Inconel	CNMA-432, H13A	CNMA-432,H13A	CNMA-432,H13A
Inconel	CNGN-434-T1, WG300	CNGN-434-T1, WG300	CNGN-434-T1, WG300
Inconel	CNMA-432-L1, CBN-20	CNMA-432-L1, CBN-20	CNMA-432-L1, CBN-20
M-50	CNGN-434-T1, WG300	CNGN-434-T1, WG300	CNGN-434-T1, WG300
M-50	CNMA-432-L1, CBN-20	CNMA-432-L1, CBN-20	CNMA-432-L1, CBN-20

Test Methodologies

Chip Control Testing

Chip control testing was performed to compare the difference in the chips produced using flood coolant and ***flojet*** when all other machining parameters were held constant. Several different combinations of speed and feed were selected for each material, with at least one condition each approximating a roughing and a finishing cut. Samples of the resulting chips were retained for comparison.

Tool Life Testing

Tool Life Curves, which plot tool life vs. cutting speed for fixed feed and depth of cut, can be used to predict tool life at a given speed, or the speed required to produce a given tool life. They are also widely used to compare the machinability of different materials or the performance of different tools. Tests were performed on all materials except the aluminum, comparing the influence of flood, ***flojet***, and ***flojet*** without CO_2 on tool life.

To generate tool life plots, a number of wear tests are conducted at different speeds at a fixed feed and depth of cut. During wear testing, the process is stopped at intervals to measure the wear on the insert and plot the wear against time (wear curves). The test is ended at a pre-determined level of wear. The wear curves are used to plot Tool Life Curves. A specific amount of wear is selected (0.015-inch uniform wear, for example) and the time to produce that wear at each tested speed is read from the wear plots. These times (life) are than plotted against speed.

Force Testing

A triaxial dynamometer was mounted in a modified tool block on the turret with the tool holder clamped in the dynamometer. The three orthogonal cutting forces were collected while cutting each of the material/tool combinations and the resultants automatically computed. The influence of flood, ***flojet***, and ***flojet*** without CO_2 on cutting force was compared. Horsepower and spindle speed were also monitored during these tests.

Surface Finish/Surface Integrity Testing

The surface finish produced using flood, and ***flojet*** without CO_2 was compared at several different cutting conditions. In each case, surface measurement figures represent the average of readings at three radially spaced locations on the bar. Metallographic samples were also prepared for each material at a single test condition to identify possible process-induced alterations in the surface of the material.

Temperature Testing

The possible effect of the CO_2 on the bulk temperature of the fluid was investigated by placing a thermocouple in the coolant sump and monitoring the temperature as ***flojet*** was run continuously with, and then without, the CO_2 turned on. The test was run until temperature equilibrium in the sump was reached. No cutting took place during these tests.

TEST RESULTS

Chip Control

For the purposes of evaluating chip forms in this study, broken, short chips are considered to be desirable. In all cases, ***flojet*** produced chip forms that were equal to or better than those produced using flood coolant at the same operating conditions – even when chip breaker designs were utilized for the flood testing. Table 3 lists the parameters used during the chip control tests, and the following photographs show some of the chips produced. In each pair of pictures, all the process parameters are the same except for the coolant application method.

Use of the ***flojet*** system produced broken, manageable chips in virtually all of the tests. However, in tests taking light cuts in 7075 aluminum long chips and "birds nests" were intermittently produced. In some cases, chip control spontaneously returned; in other cases, manual chip clearing was required.

There were also several instances of poor chip control during tool life testing of the titanium. The tests were run at 0.100-inch depth of cut and 0.006-inch/rev. feed. Birds nests developed at several different speeds. In most of the titanium tests, nose wear was the predominant wear mechanism and the length of the chip increased with wear. In each case chip control was lost at nose wear levels of 0.015-0.016-inch, although in other cases chip control was retained to 0.030-inch nose wear.

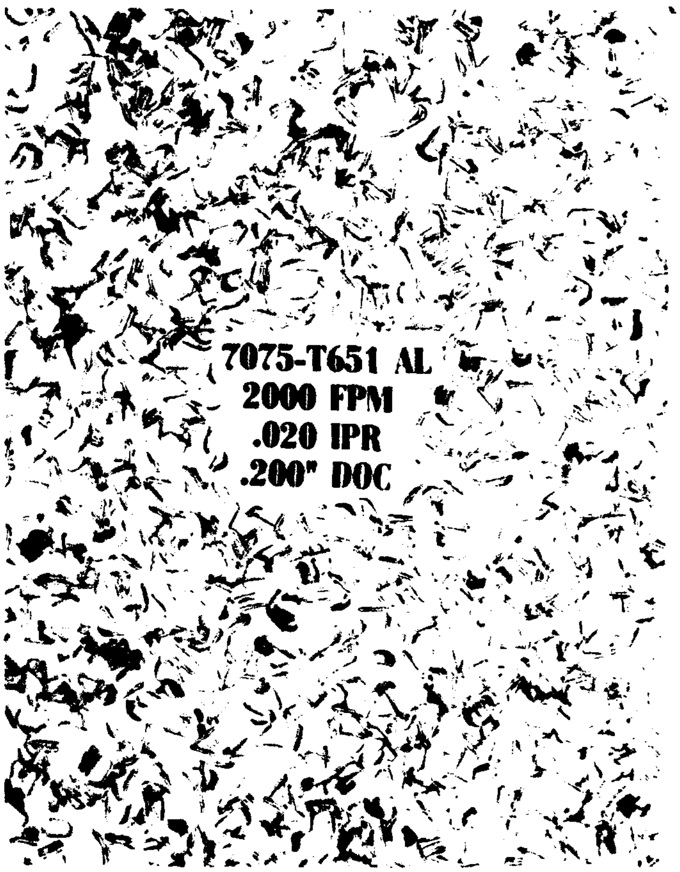
Whenever chip control was lost or intermittent during ***flojet*** testing, correct system operation and nozzle alignment were checked and confirmed. Other than the noted occurrences in the tool life testing of titanium, there were no other cases of poor chip control using ***flojet*** in other tests during this program.

Table 3 — Chip Control Test Parameters

MATERIAL	SPEED (sfm)	FEED (ipr)	DEPTH OF CUT (inches)
Aluminum	2000 2000	.020 .002	.200 .030
4340 Steel	500 500 500 500 500	.020 .010 .005 .010 .005	.125 .125 .125 .030 .030
17-4 Stainless	500 500 500 500	.020 .010 .005 .005	.125 .125 .125 .030
Titanium	100 100 100 100 100	.020 .015 .005 .015 .010	.100 .100 .100 .030 .030
Inconel	100 100 100 100 100	.015 .010 .005 .010 .005	.100 .100 .100 .030 .030
M-50			

CHIP CONTROL TEST RESULTS

FLOOD COOLANT



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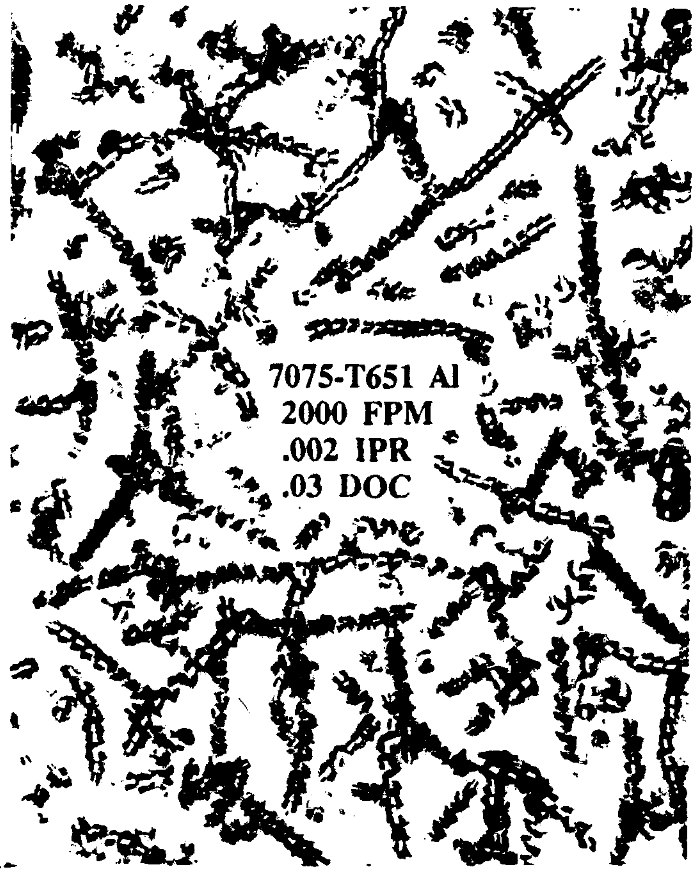
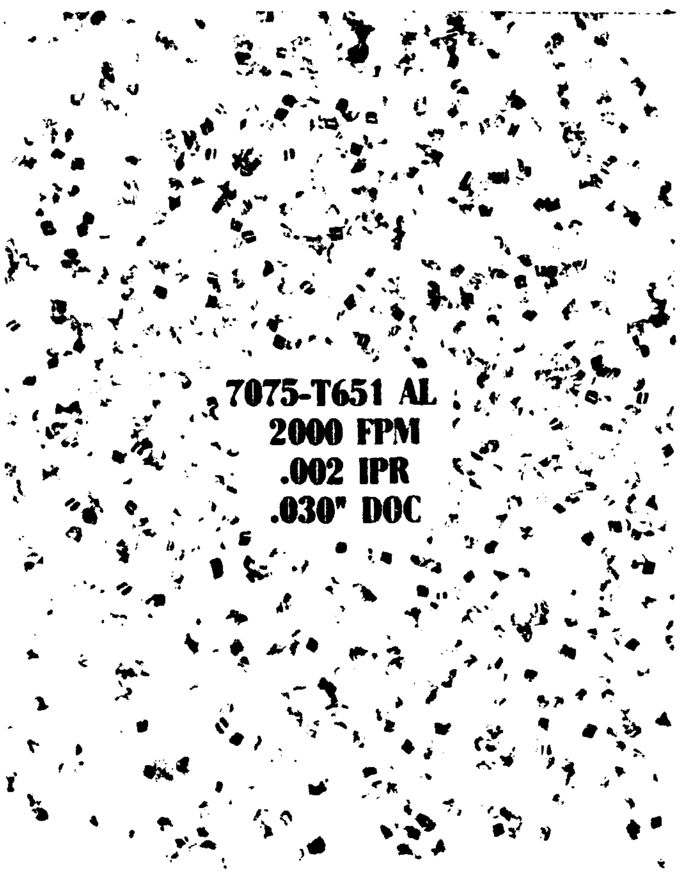
CHIP CONTROL TEST RESULTS

FLOOD COOLANT





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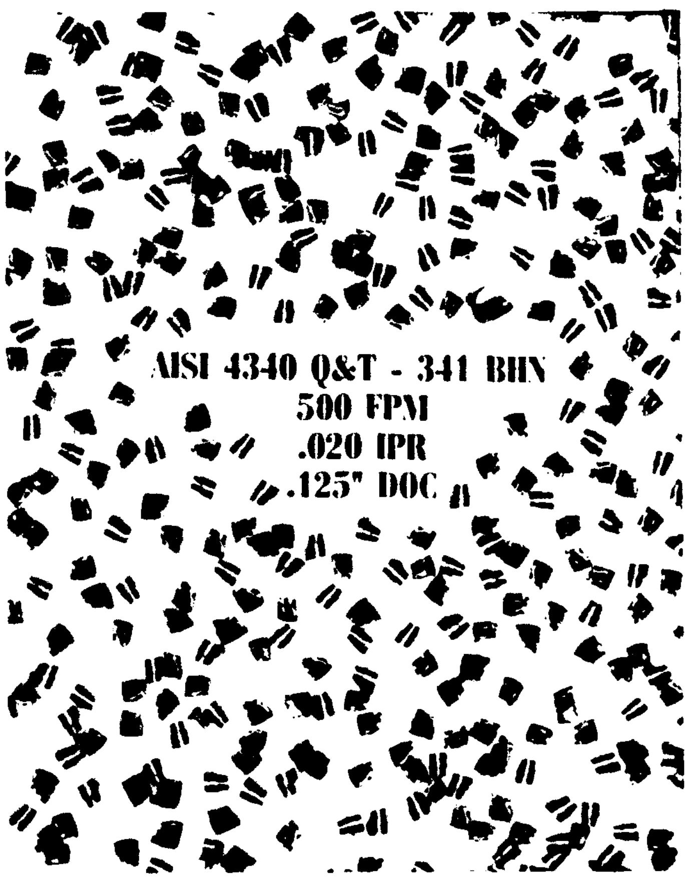
CHIP CONTROL TEST RESULTS

FLOOD COOLANT



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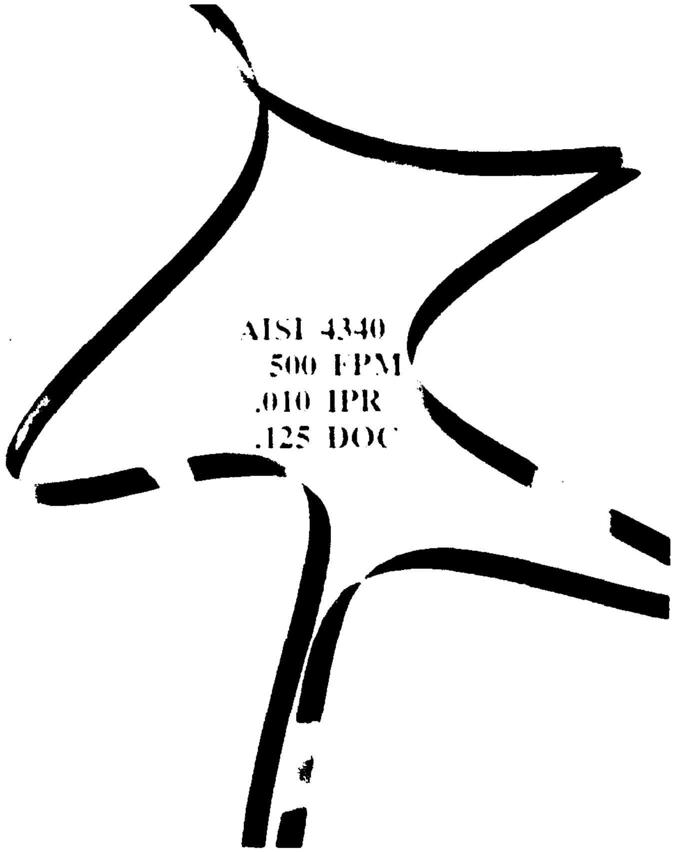
CHIP CONTROL TEST RESULTS

FLOOD COOLANT



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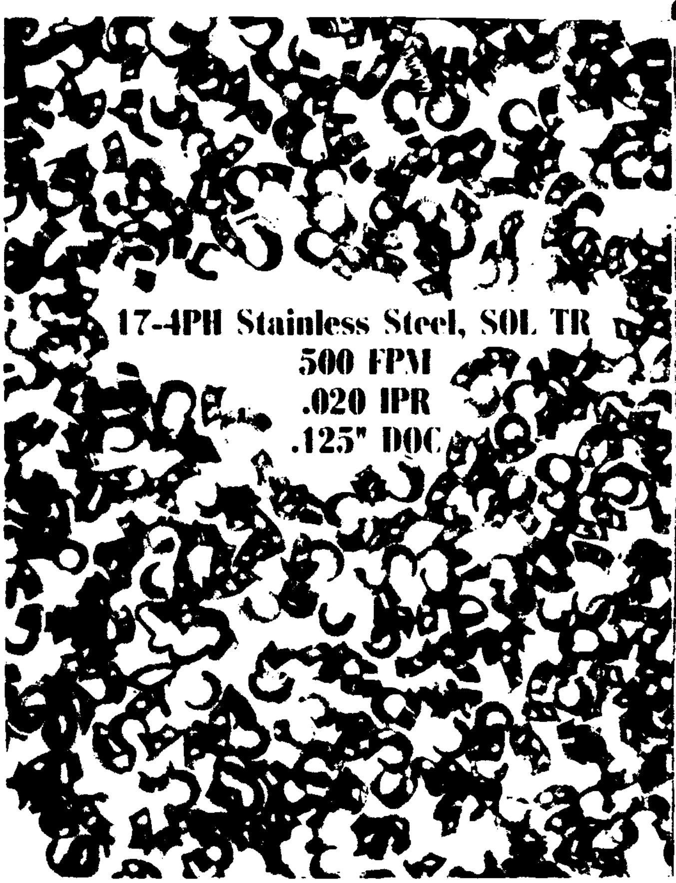
CHIP CONTROL TEST RESULTS

FLOOD COOLANT



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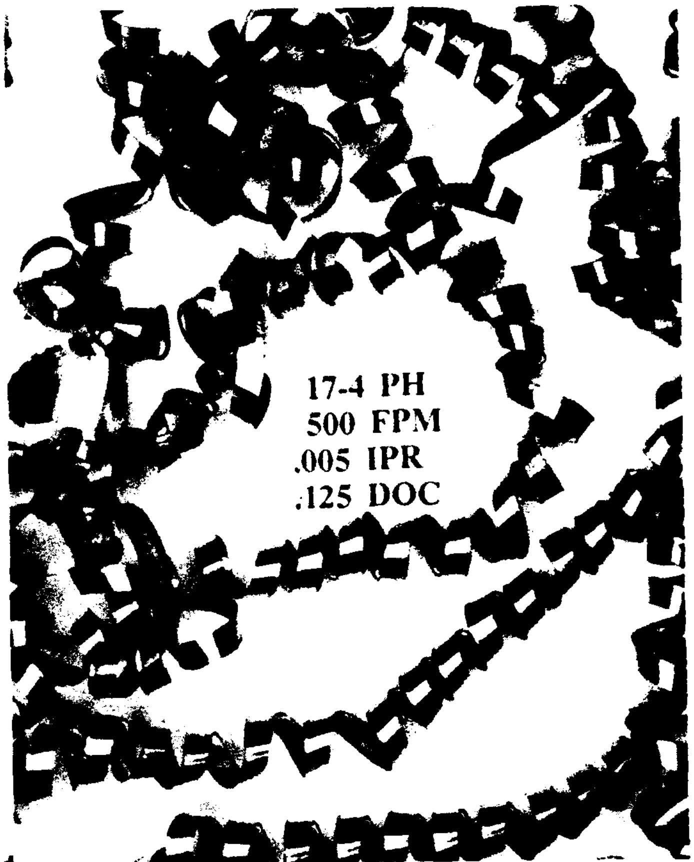
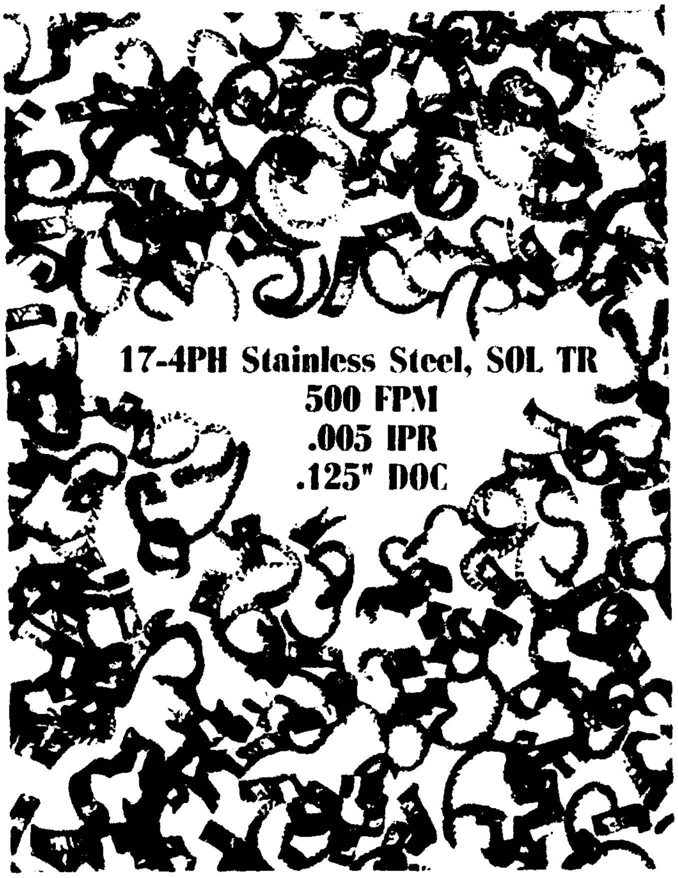
CHIP CONTROL TEST RESULTS

FLOOD COOLANT





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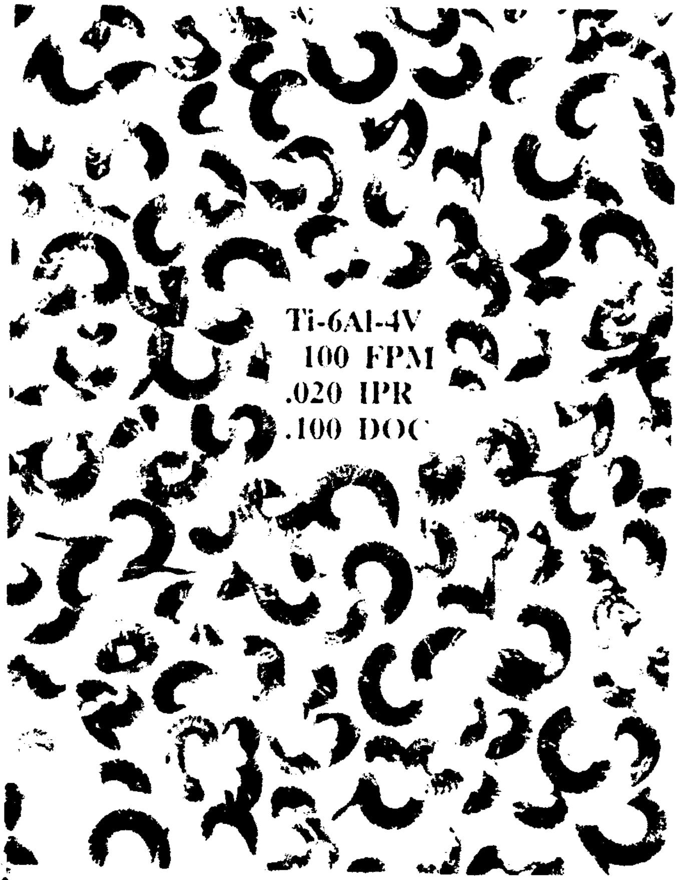
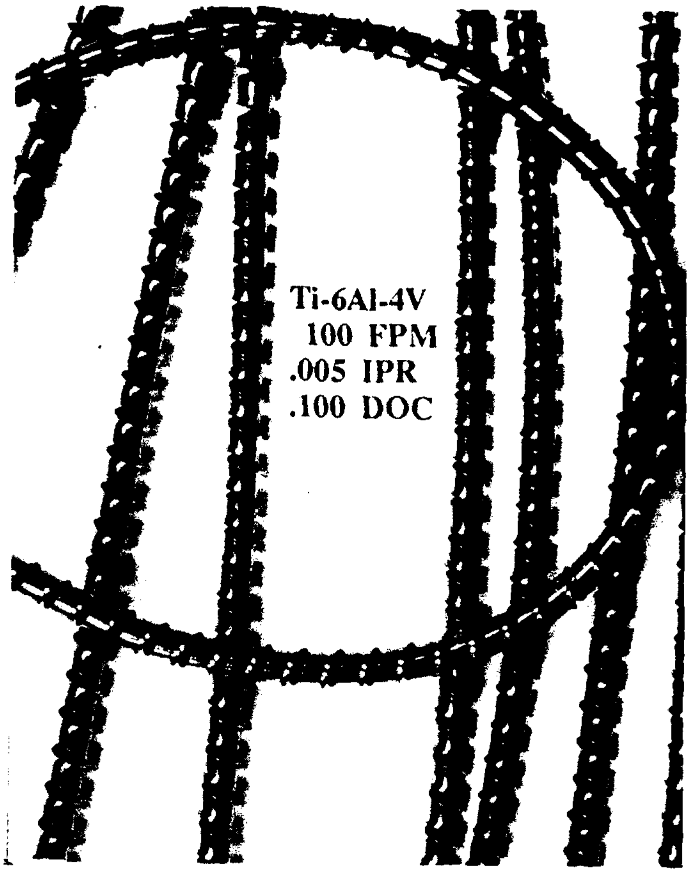
CHIP CONTROL TEST RESULTS



FLOOD COOLANT

flojet

CHIP CONTROL TEST RESULTS



FLOOD COOLANT

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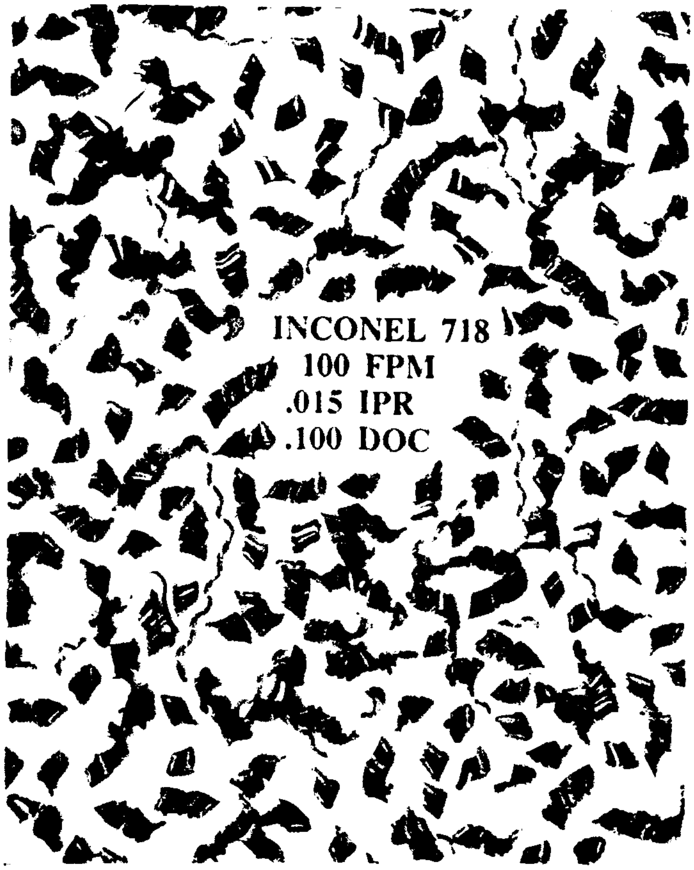
CHIP CONTROL TEST RESULTS

FLOOD COOLANT



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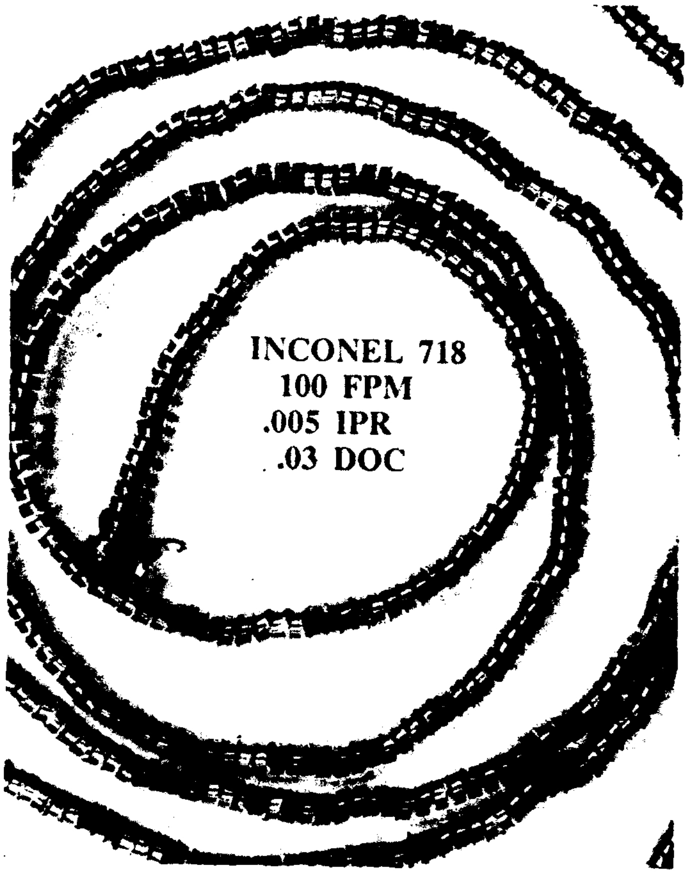
CHIP CONTROL TEST RESULTS



FLOOD COOLANT

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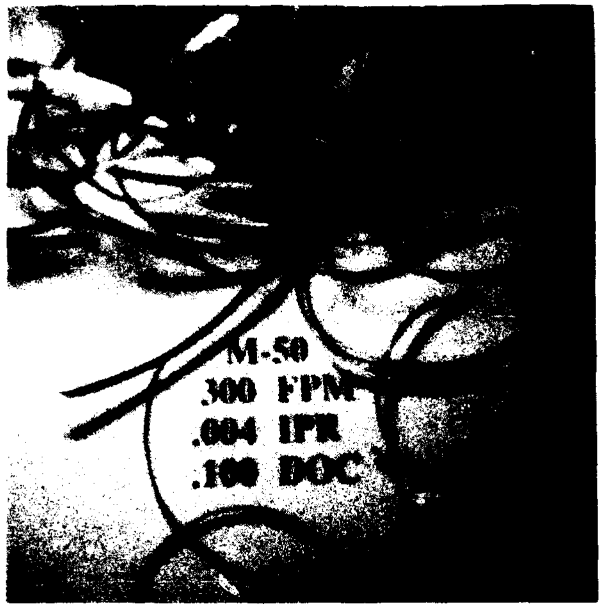
CHIP CONTROL TEST RESULTS

FLOOD COOLANT



flojet

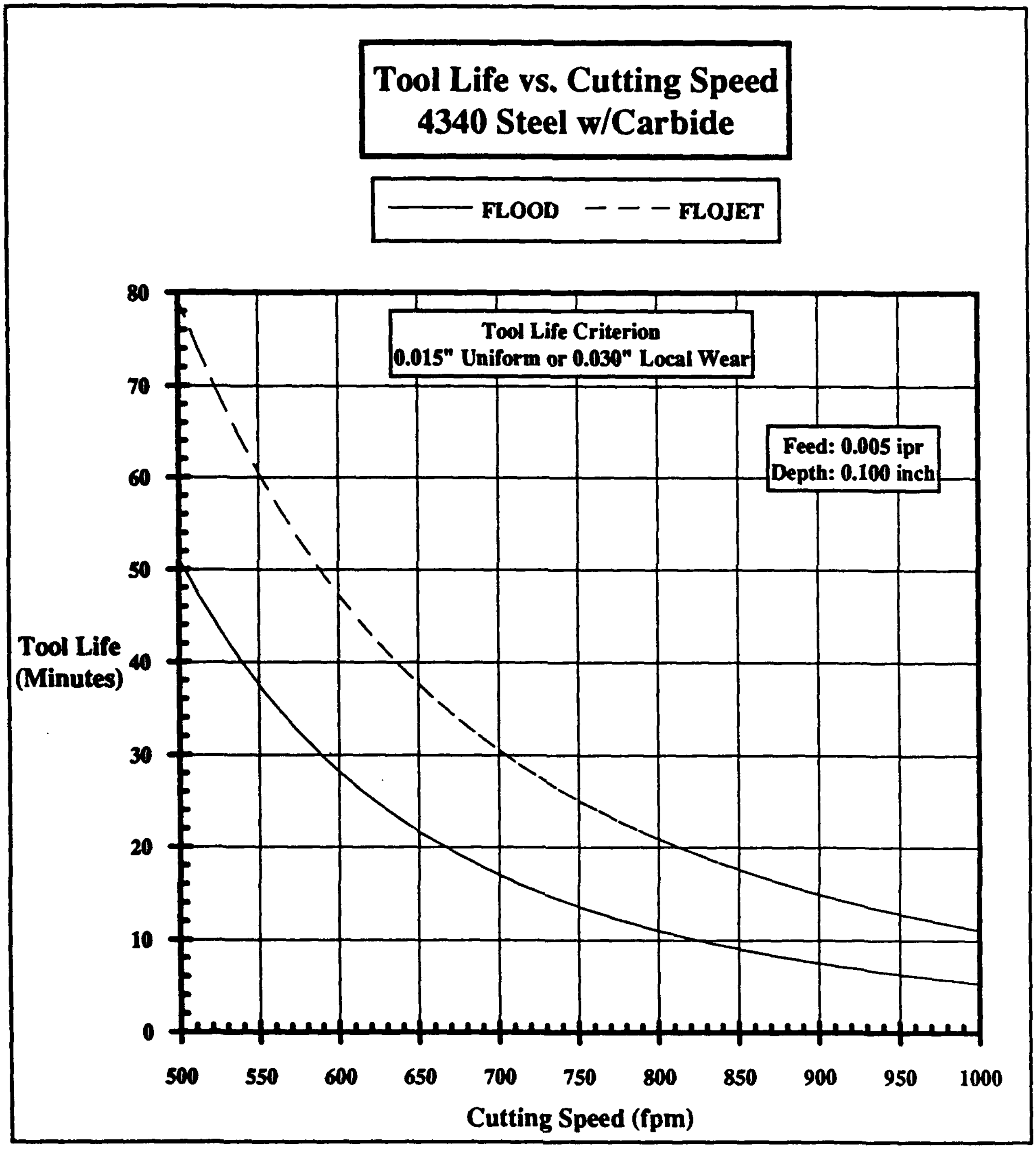
Tool Life

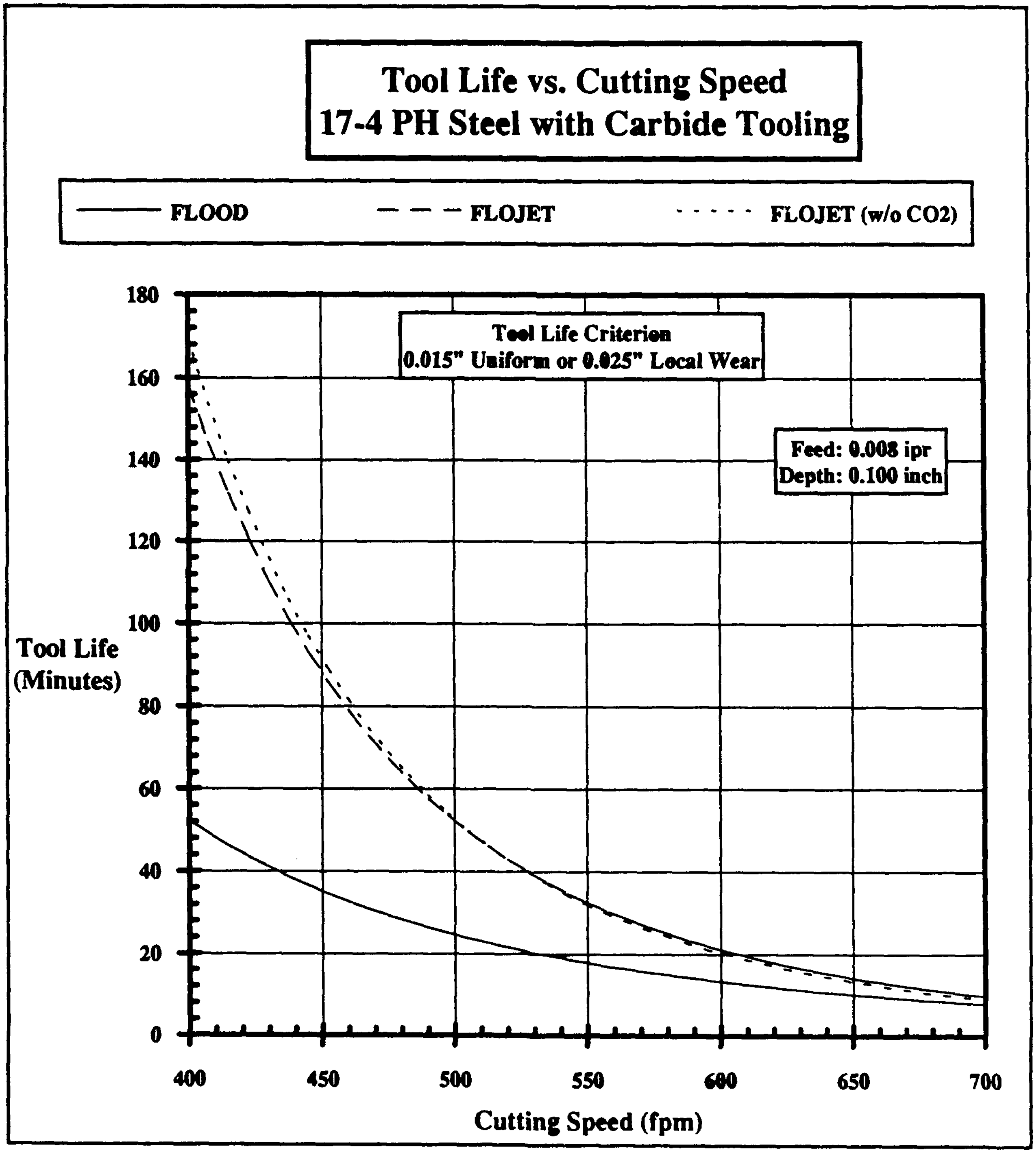
Tool life tests were performed on all materials except the aluminum, comparing the influence of flood, ***flojet***, and ***flojet*** without CO_2. The results of these tests are summarized by the Tool Life Plots on the following pages. Note that the life criteria is listed at the top of the graph for each data set. The tool life criteria was selected based on the nature of the tool wear for each test. The data points used to fit the curves are included as APPENDIX B. APPENDIX C contains photographs of typical wear patterns for the different material/tool combinations.

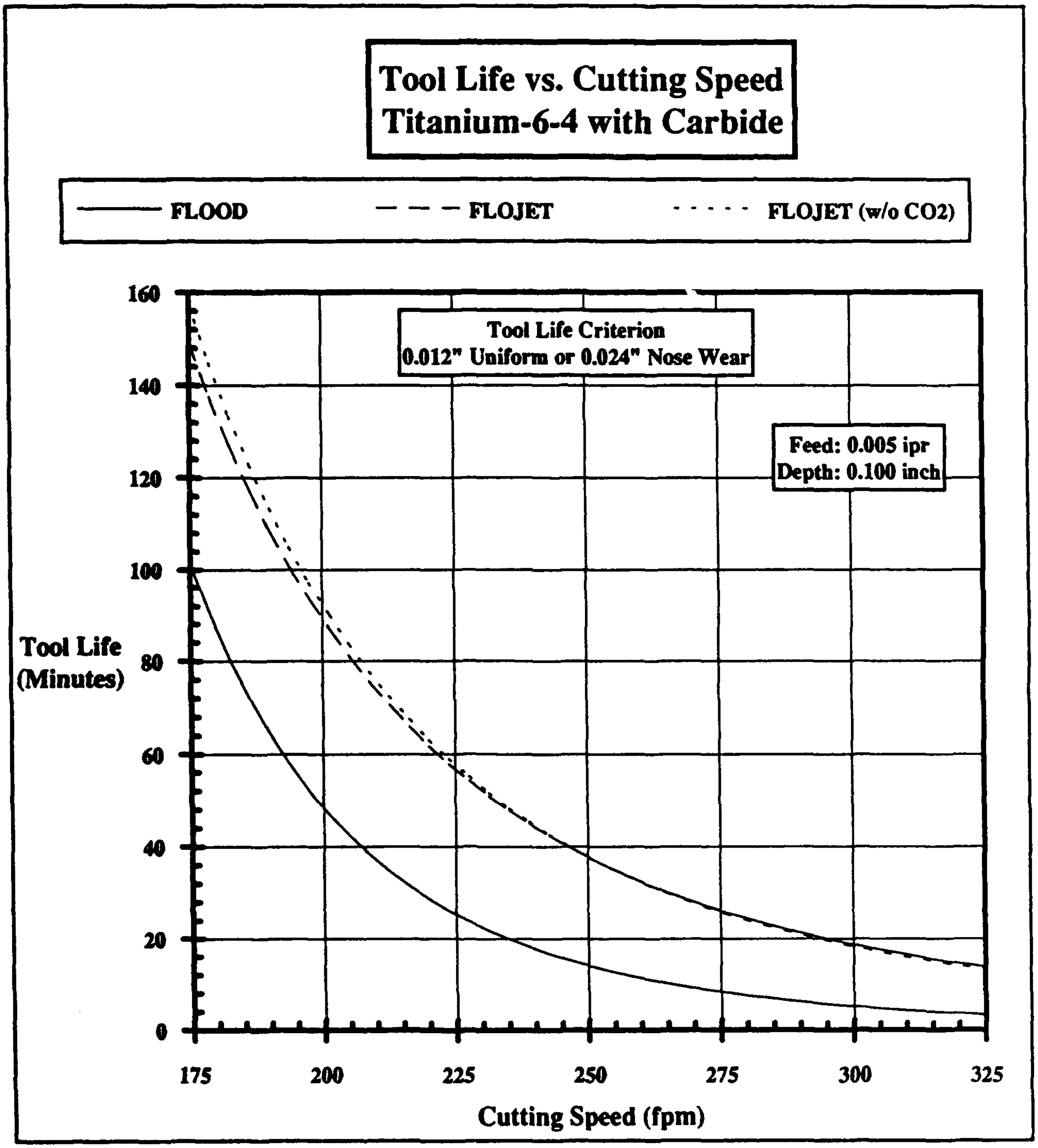
Significant tool life improvement of about two times the flood values was achieved for each of the tests using carbide inserts (4340, 17-4, titanium, and inconel). No significant effect is noted for either ceramic or CBN tools in machining the M-50, or for the CBN tools in inconel. Use of the ***flojet*** system when machining inconel with the ceramic tools resulted in decreased tool life.

There is no significant difference in tool life performance between ***flojet*** and ***flojet*** without CO_2 for any of the tested material/tool combinations. There was also no difference noted in the chip samples collected during tool life testing.

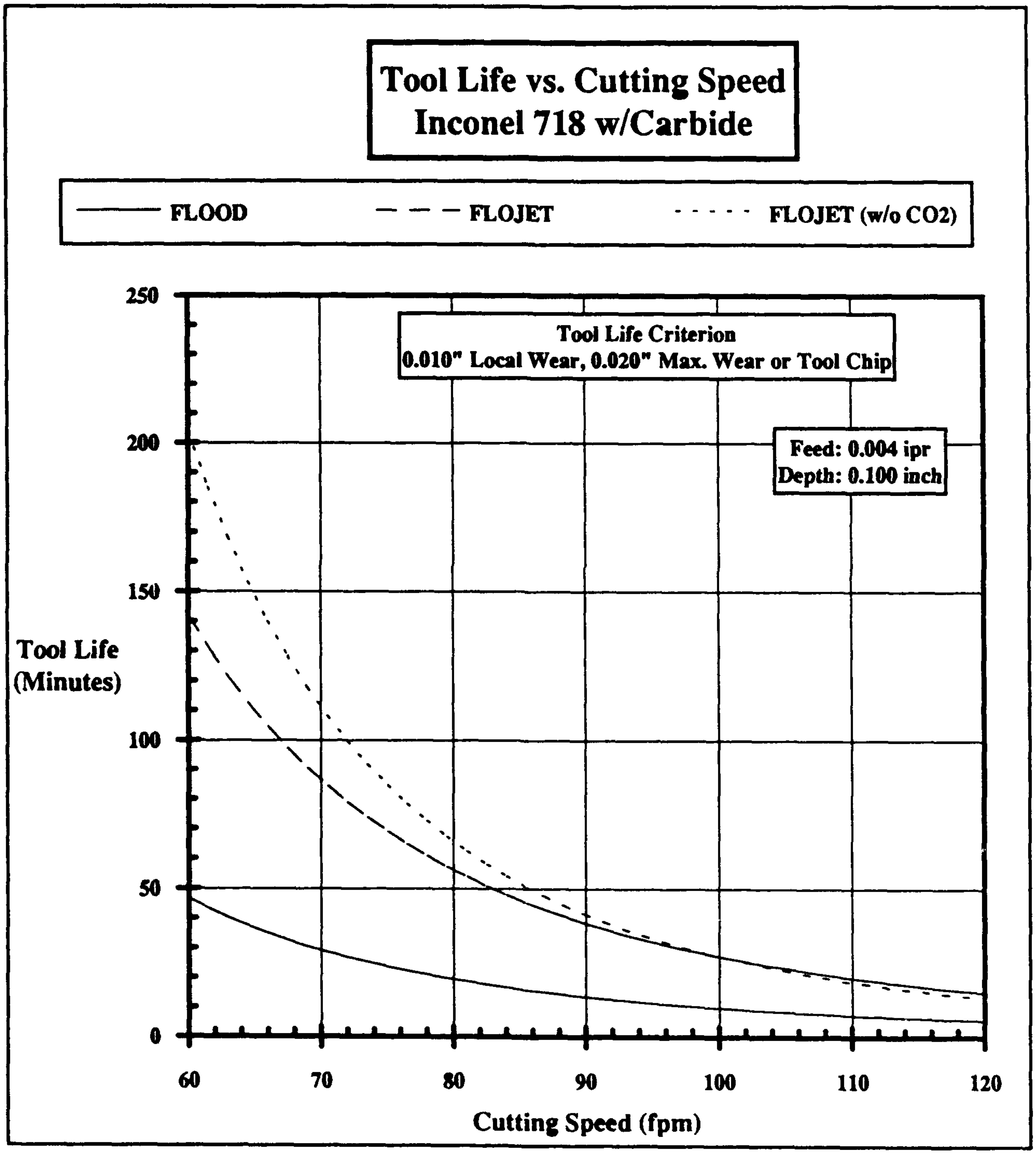
Note that there is no "***flojet*** without CO_2" curve plotted for the 4340 steel. The initial lot of this material was exhausted during testing with CO_2, and although the next lot had identical specifications and hardness, analysis of the collected data showed it to have significantly different machinability. For this reason, the data collected on the second lot of material, including the testing without CO_2, can not be compared.

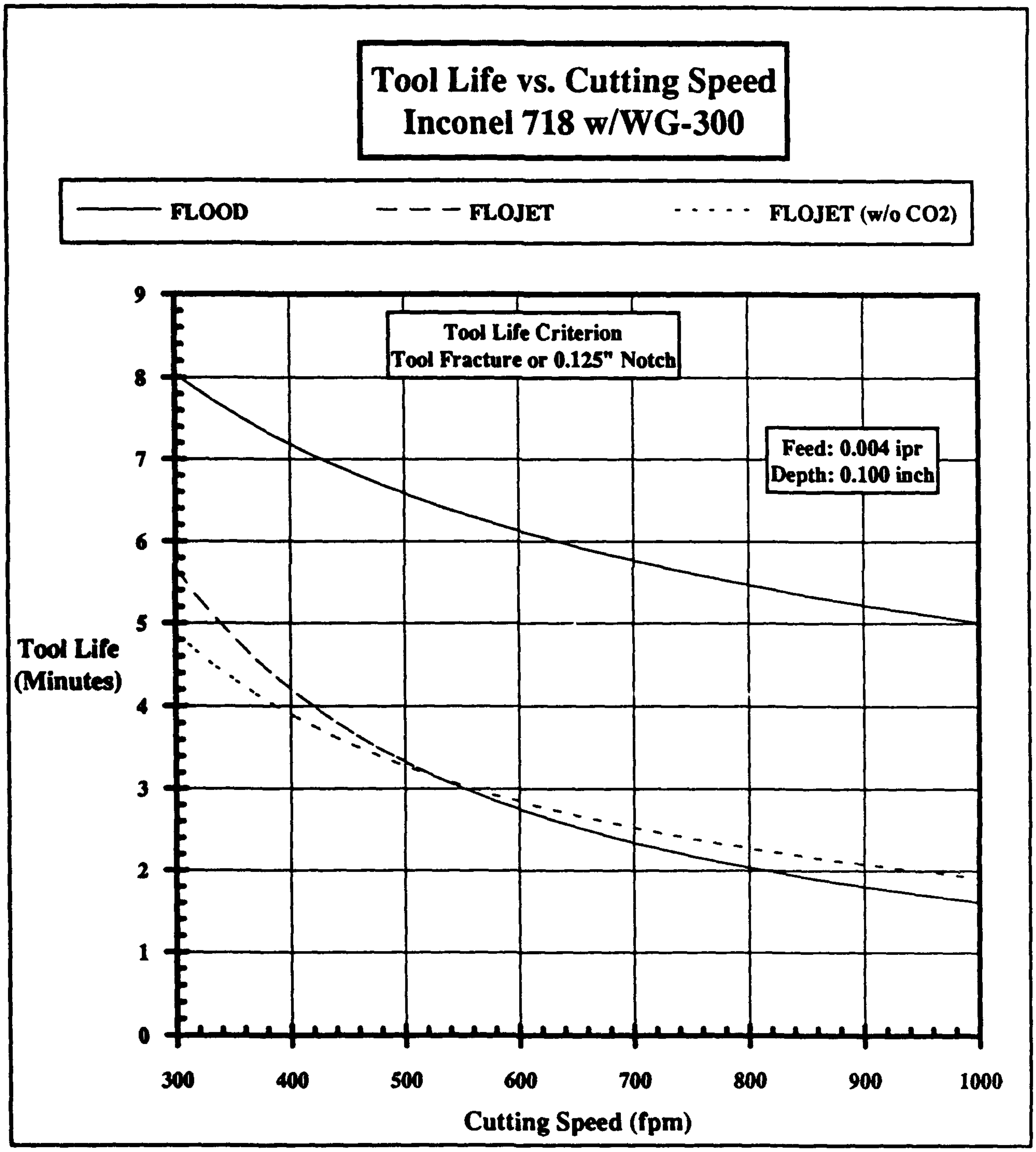

Tool Life vs. Cutting Speed
4340 Steel w/Carbide
FLOOD
FLOJET
Tool Life Criterion
0.015" Uniform or 0.030" Local Wear
Feed: 0.005 ipr
Depth: 0.100 inch
Tool Life (Minutes)
0
10
20
30
40
50
60
70
80
500
550
600
650
700
750
800
850
900
950
1000
Cutting Speed (fpm)


Tool Life vs. Cutting Speed
17-4 PH Steel with Carbide Tooling
FLOOD
FLOJET
FLOJET (w/o CO2)
Tool Life Criterion
0.015" Uniform or 0.025" Local Wear
Feed: 0.008 ipr
Depth: 0.100 inch
Tool Life (Minutes)
180
160
140
120
100
80
60
40
20
0
400
450
500
550
600
650
700
Cutting Speed (fpm)

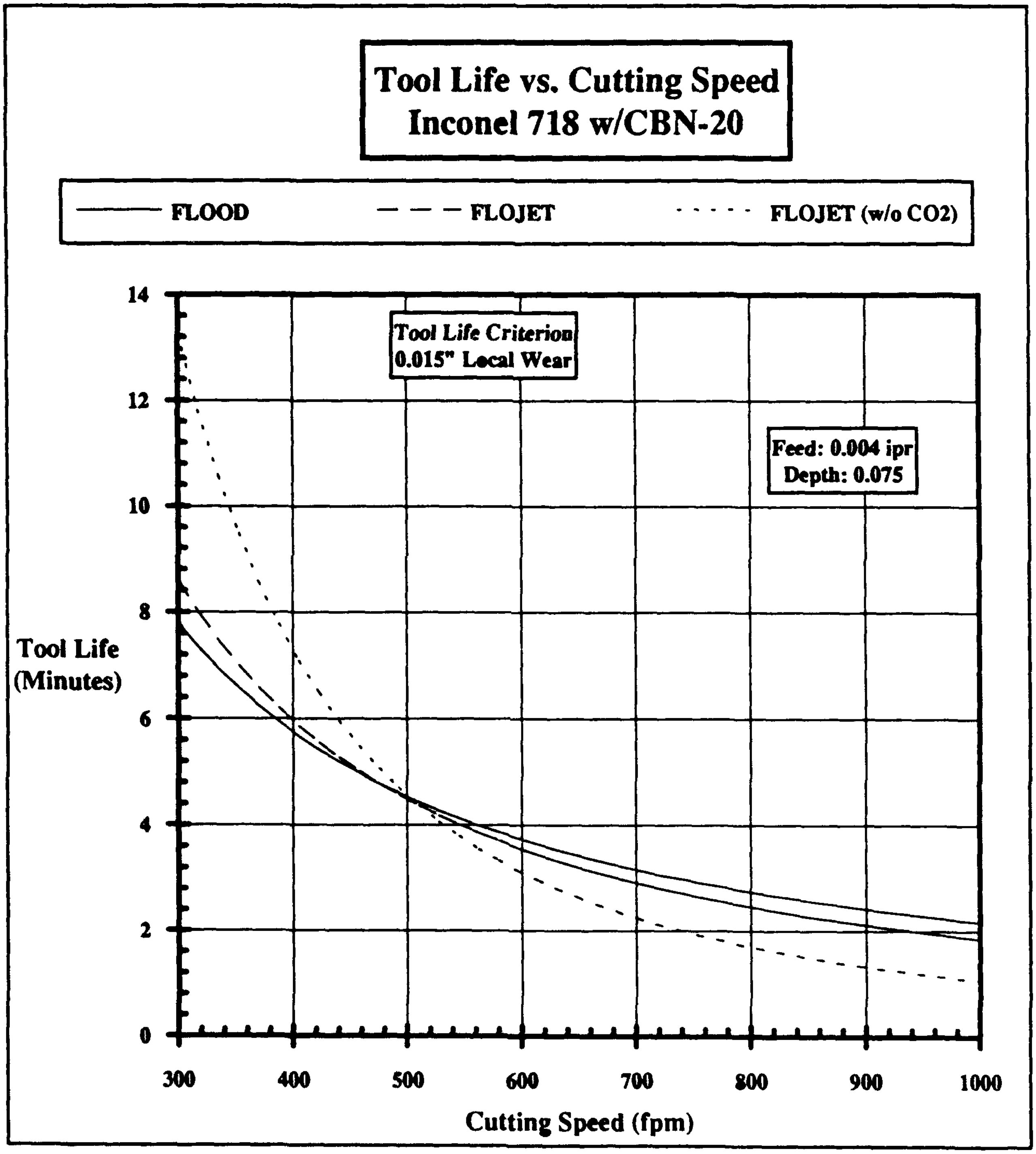


Tool Life vs. Cutting Speed
Titanium-6-4 with Carbide
FLOOD
FLOJET
FLOJET (w/o CO2)
Tool Life Criterion
0.012" Uniform or 0.024" Nose Wear
Feed: 0.005 ipr
Depth: 0.100 inch
Tool Life (Minutes)
0
20
40
60
80
100
120
140
160
175
200
225
250
275
300
325
Cutting Speed (fpm)

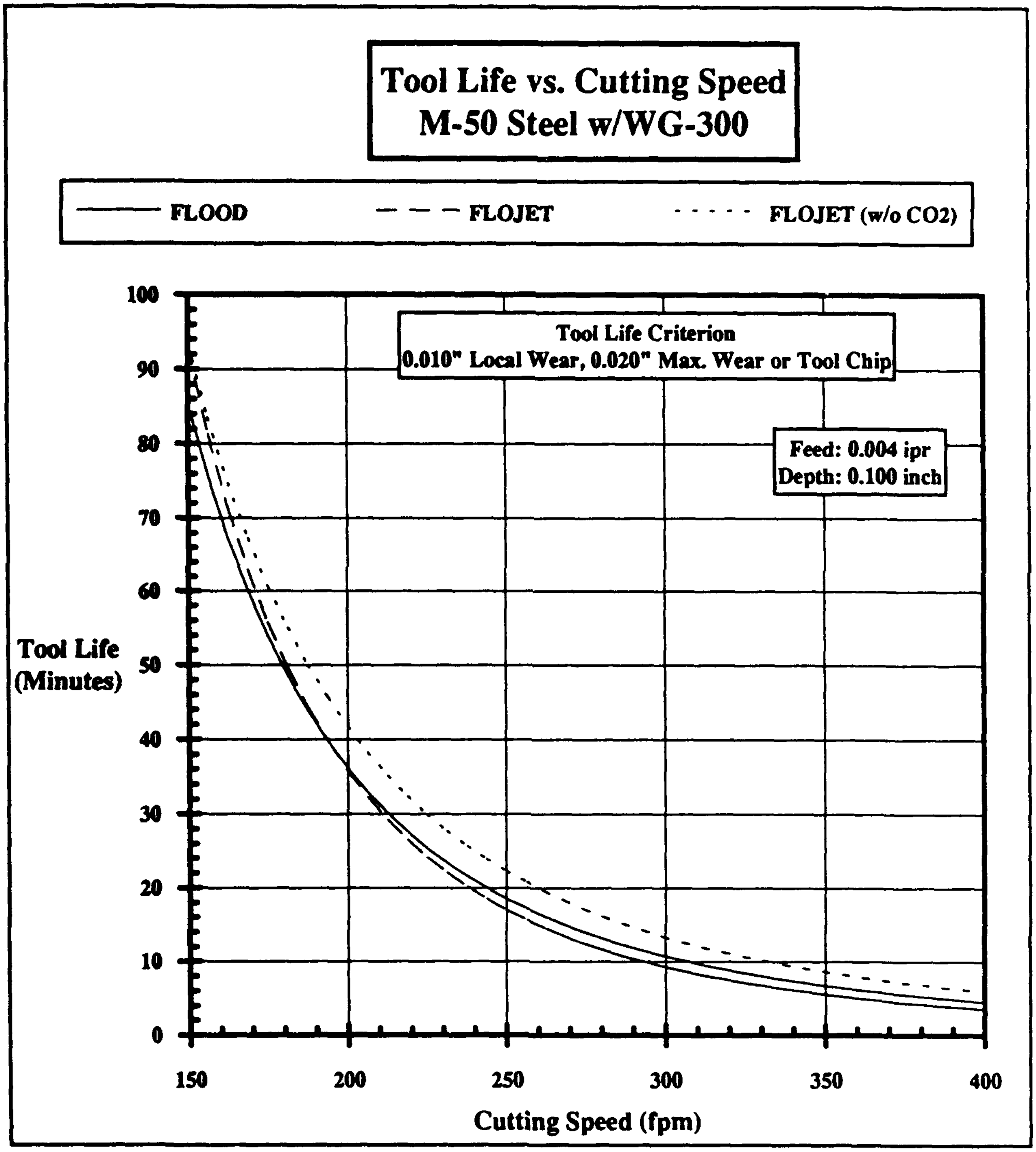

Tool Life vs. Cutting Speed
Inconel 718 w/Carbide
FLOOD
FLOJET
FLOJET (w/o CO2)
Tool Life Criterion
0.010" Local Wear, 0.020" Max. Wear or Tool Chip
Feed: 0.004 ipr
Depth: 0.100 inch
Tool Life
(Minutes)
250
200
150
100
50
0
60
70
80
90
100
110
120
Cutting Speed (fpm)

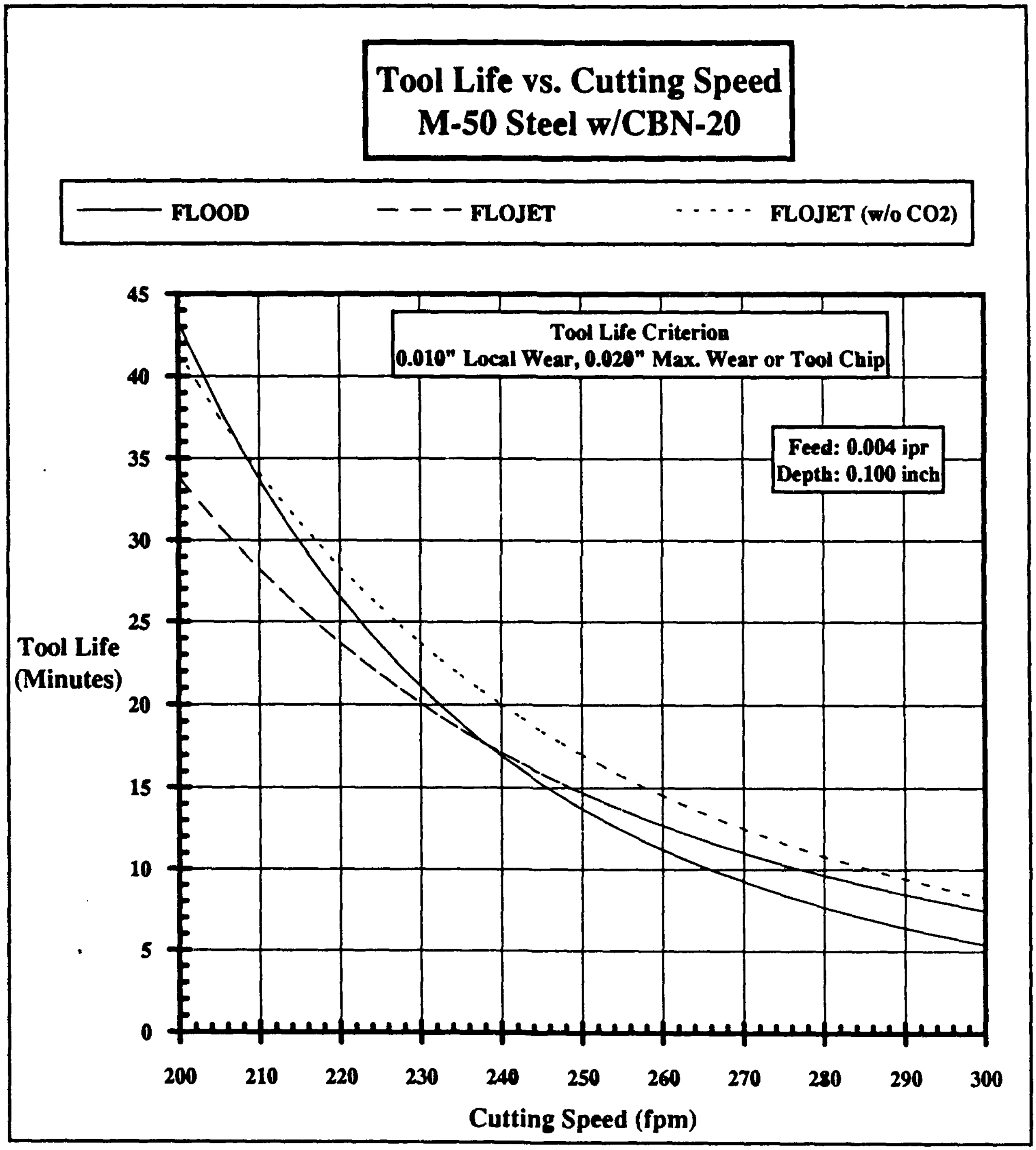


Tool Life vs. Cutting Speed
Inconel 718 w/WG-300
FLOOD
FLOJET
FLOJET (w/o CO2)
Tool Life Criterion
Tool Fracture or 0.125" Notch
Feed: 0.004 ipr
Depth: 0.100 inch
Tool Life (Minutes)
0
1
2
3
4
5
6
7
8
9
300
400
500
600
700
800
900
1000
Cutting Speed (fpm)



Tool Life vs. Cutting Speed
Inconel 718 w/CBN-20
FLOOD
FLOJET
FLOJET (w/o CO2)
Tool Life Criterion
0.015" Local Wear
Feed: 0.004 ipr
Depth: 0.075
Tool Life (Minutes)
0
2
4
6
8
10
12
14
300
400
500
600
700
800
900
1000
Cutting Speed (fpm)


Tool Life vs. Cutting Speed
M-50 Steel w/WG-300
FLOOD
FLOJET
FLOJET (w/o CO2)
Tool Life Criterion
0.010" Local Wear, 0.020" Max. Wear or Tool Chip
Feed: 0.004 ipr
Depth: 0.100 inch
Tool Life (Minutes)
0
10
20
30
40
50
60
70
80
90
100
150
200
250
300
350
400
Cutting Speed (fpm)


Tool Life vs. Cutting Speed
M-50 Steel w/CBN-20
FLOOD
FLOJET
FLOJET (w/o CO2)
Tool Life Criterion
0.010" Local Wear, 0.020" Max. Wear or Tool Chip
Feed: 0.004 ipr
Depth: 0.100 inch
Tool Life (Minutes)
45
40
35
30
25
20
15
10
5
0
200
210
220
230
240
250
260
270
280
290
300
Cutting Speed (fpm)

Force and Horsepower

Table 4 summarizes the test conditions used to investigate the effect of ***flojet*** on cutting force and horsepower. Each test condition was run using flood, ***flojet***, and ***flojet*** without CO_2. The data collected during these tests is included as APPENDIX D. A resultant cutting force can be calculated from the orthogonal force data and a typical example is shown on the following page (Figure 2). A single insert was used for all three passes except when cutting the inconel and M-50, the gradual slope of the force curves when they are plotted together is indicative of the cumulative tool wear. A new insert was used for each pass on the inconel and M-50. An effect due to the type of coolant application would be indicated by a significant change in the force value between the end of one test and the beginning of the next. The complete set of resultant force plots are presented in APPENDIX E.

Table 4 – Force Test Parameters

Material	Test	Insert	Depth (Inches)	Speed (fpm	Feed (Inches)
Aluminum	1	Carbide	.100	1500	.005
	2			1500	.015
	3			2500	.005
4340	1	Carbide	.100	500	.005
	2			500	.012
	3			900	.005
17-4	1	Carbide	.100	450	.008
	2			450	.015
	3			600	.008
Titanium	1	Carbide	.100	200	.006
	2			200	.015
	3			260	.006
Inconel	1	Carbide	.100	90	.004
	2			40	.008
	3			110	.004
	4	Ceramic	.100	800	.004
	5			500	004
M-50	1	Ceramic	.100	250	.004
	2			250	.008
	3			400	.004
	4	CBN	.100	250	.004

There is no significant effect on the base cutting force or horsepower due to ***flojet*** for any of the conditions tested. The effect of increasing the tool life can be noted on several of the plots where the slope of the force curve is less with ***flojet*** than with flood coolant, indicating a slower rate of tool wear.

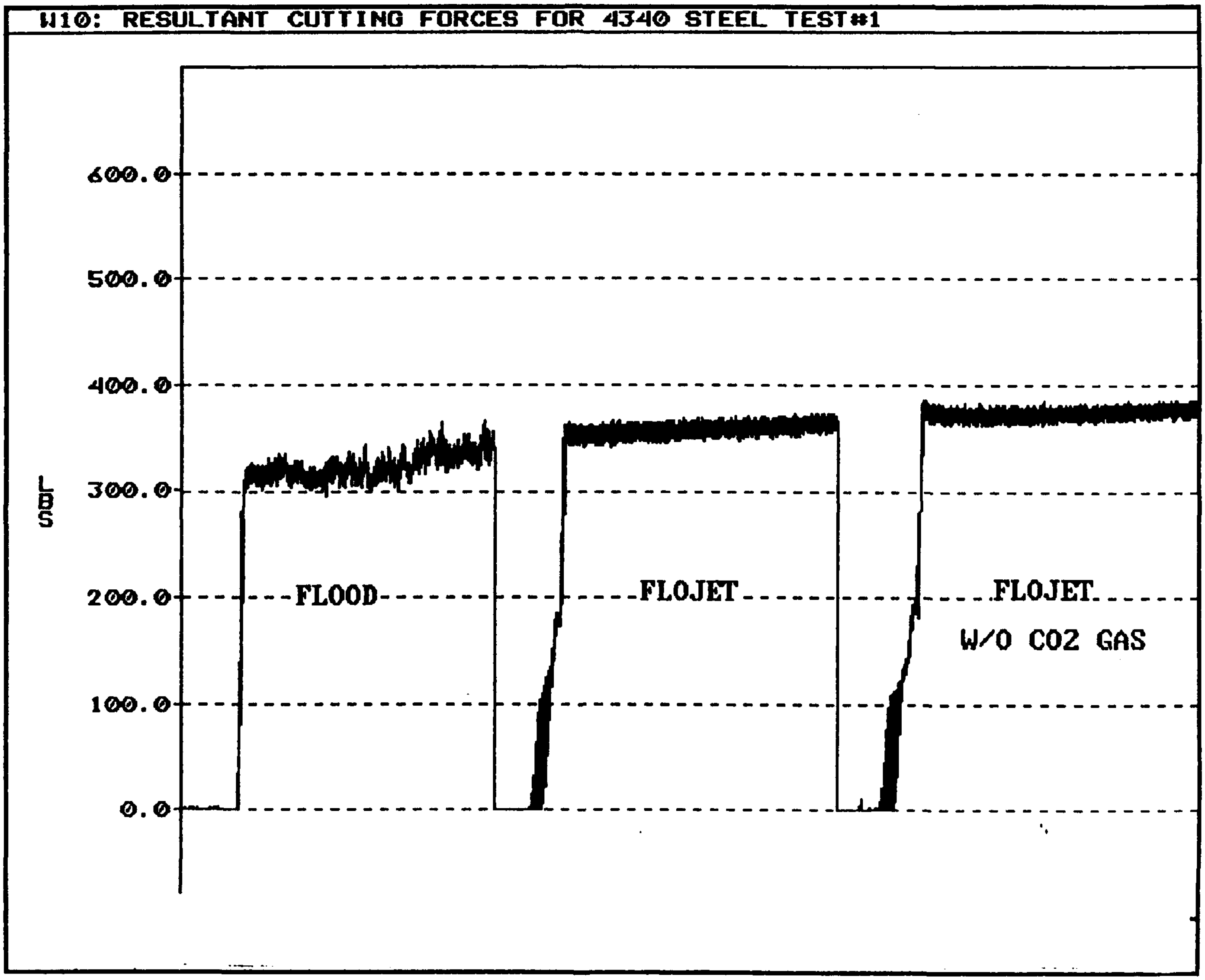


Figure 2 - Typical Resultant Force Plot

Surface Finish and Surface Integrity

Table 5 summarizes the surface finish test matrix and results. Portions of some of the test bars were cut and mounted and examined under a microscope to determine if using the ***flojet*** system has any effect on the surface condition of the material. The metallography report is attached as APPENDIX F.

No significant effect on surface finish due to ***flojet*** is noted for any of the conditions tested. Metallographic analysis does not indicate any material effect due to ***flojet***.

Bulk Temperature

Figure 3 shows a plot of coolant sump temperature vs. time for flood, ***flojet***, and ***flojet*** without CO_2. This data represents the coolant system running continuously until a steady state temperature is achieved and is intended to identify any effect that the CO_2 has on the bulk coolant temperature. It does not measure any effect that the gas may have on the temperature in the cutting zone. Each test was run at the beginning of the day with the machine at ambient temperature. Note the slight difference in ambient temperature between the tests of ***flojet*** with and without the gas.

No effect on the bulk coolant temperature can be attributed to the use of the CO_2 gas.

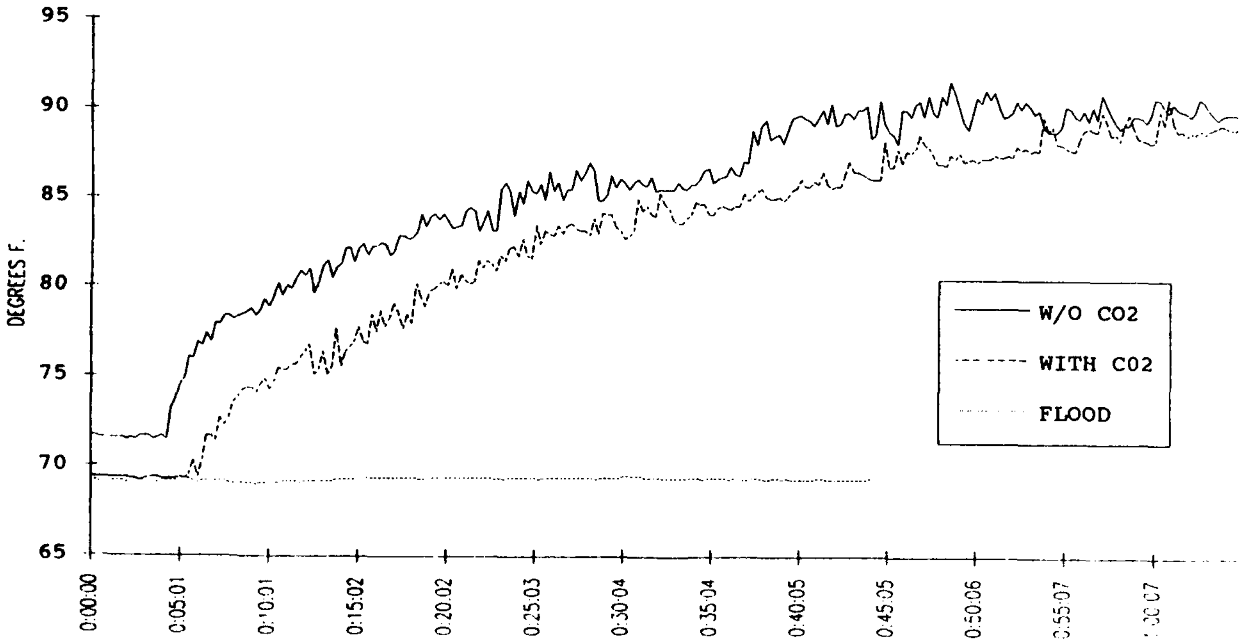


Figure 3 - Coolant Sump Temperature

Table 5

SURFACE FINISH MEASUREMENTS (R_a)						
MATERIAL	INSERT	SPEED (sfpm)	FEED (ipr)	FLOOD COOLANT	FLOJET	FLOJET W/O CO_2
4340	CNMA-432 Grade: 415	500	0.005	34	32	45
		500	0.012	90	82	86
		900	0.005	24	31	35
17-4 PH	CNMA-432 Grade: 415	450	0.008	61	58	56
		450	0.015	99	92	95
		600	0.008	70	60	55
Ti-6Al-4V	CNMA-432 Grade: H13A	200	0.006	28	34	34
		200	0.015	142	141	140
		260	0.006	23	41	48
Al-7075	CNMA-432 Grade: K68	1500	0.005	33	31	36
		1500	0.015	133	132	134
		2500	0.005	30	34	33
Inconel-718	CNMA-432 Grade: H13A	90	0.004	21	24	26
		90	0.008	48	70	73
		110	0.004	29	30	33
	CNGN-434-T1 Grade: WG-300	800	0.004	41	40	48
	CNMA-432L1 Grade: CBN-20	500	0.004	18	23	na
M-50	CNGN-434-T1 Grade: WG-300	250	0.004	30	40	31
		250	0.008	na	na	na
		400	0.004	24	35	25
	CNMA-432L1 Grade: CBN-20	250	0.004	21	28	na

ECONOMIC VALUE ANALYSIS OF SYSTEM

Objective

The objective of this portion of the program was to assess the economic value the ***flojet*** system may provide in typical industrial environments. Specifically, this effort provided:

- An approach to evaluate the ***flojet*** system that would be usable in a variety of industrial situations.
- A listing of the potential tangible and intangible benefits and costs ***flojet*** may provide under various industrial contexts.
- Sample evaluations of the ***flojet*** cost/benefits utilizing the laboratory data developed in this program.
- Conclusions as to the general viability of the ***flojet*** process.

The analysis presented is intended to provide industry with general guidelines and an approach to determine the economic impact ***flojet*** may have in their specific context. The economic factors utilized were selected as "reasonable" and should be replaced with actual data for specific cases, as appropriate.

Approach

The approach taken to evaluate the ***flojet*** system is summarized as follows:

- Identify the industrial context in which ***flojet*** appears to offer economic potential.
- Identify the strategies which ***flojet*** would be employed.
- Build a cost model incorporating the ***flojet*** tangible benefits and costs.
- Use the cost model to determine whether ***flojet*** provides a net savings. A positive net savings indicates that the ***flojet*** was economically feasible.
- Consider the intangible benefits as offsetting start-up risks and marginal tangible "return-on-investment' or "payback" calculations.

This approach and the results presented in this report assume the laboratory data is representative of industrial performance.

Industrial Context

Due to the increased setup time required for ***flojet*** operation, (nozzle design and adjustments and process parameter fine-tuning), the industrial context that ***flojet*** should initially be considered include:

- Medium to long production.
- Well established part families with constant setups (turning of shafts).
- Transfer Line stations adequately engineered for fluid retention.
- Situations where chip control is required and otherwise not possible with established techniques.

Industrial Usage Strategy

Assuming that one of the above industrial context applies, several strategies for using ***flojet*** may be used. Discussions were held with the ***flojet*** vendor, several ***flojet*** industrial users, and several machine tool supplies to identify ***flojet*** usage strategies. As a result, two general strategies for utilizing ***flojet*** have been identified and will be used in this analysis. These are:

- <u>STANDARD FLOJET</u>: Upgrade an individual turning center with a ***flojet*** system and continue to run the machine with an operator. The nominal strategy assumes one shift operation, one operator per two machines, and sufficient production volume taking advantage of the ***flojet*** tangible benefits (chip control and tool life extension).

- <u>UNATTENDED FLOJET</u>: Reliable chip control is the remaining technical hurdle preventing the utilization of an unattended machining strategy. All other factors, both technical (part and tool handling) and capacity (production demand and N/C support, etc.), are satisfied. Sufficient production volume is assumed. The nominal strategy assumes a two-shift operation with token direct and indirect labor attention required.

The economics of each of these strategies will be analyzed to demonstrate the industrial value of ***flojet***.

Potential *flojet* Benefits

The following list of benefits is intended to be representative. Additional benefits may be identified in specific industrial situations. The benefits are grouped as tangible and intangible.

The potential tangible (measurable) economic benefits of ***flojet*** are:

- Longer tool life at the same cutting speed (lab data indicates a doubling of tool life).
- Higher cutting speeds with equal tool life.
- Reduced downtime due to chip removal.
- Improved surface finish (limited cases).

Clearly, the best approach is to combine benefits 1) and 2) and achieve somewhat longer tool life at higher speeds. The "best" combination of cutting speed and tool life is found by utilizing the classical machining economic model, which considers the ratio of tool cost and machine time cost.

The potential intangible economic benefits of ***flojet*** are:

- Universal chip control across multiple materials, wide feed/depth ranges, and with standard tool geometries.

- Increased safety due to the elimination of manual handling of long, stringy chips.
- Reduced tooling inventory due to the elimination of chipbreaker geometries.
- Improved process quality and reliability via automation with chips under control.

Clearly, in certain production situations the intangible benefits may outweigh any other considerations. For example, if part quality is compromised without chip control, and there is no other practical means to obtain reliable chip control, then the investment in ***flojet*** is justified on the quality issue alone. The same argument can be made for operator safety with respect to worker injury, loss time, and insurance claims.

Additional *flojet* Costs

The following list of costs are intended to be representative. The additional ***flojet*** costs identified are as follows:

<u>Depreciation</u>

- ***flojet*** system (including installation costs)
- end effectors/tooling blocks (as needed)
- mist collection unit (required)

Operating Costs

- CO_2 usage — ($1.50 per cutting hour)
- *flojet* filters — ($0.50 per cutting hour)
- *flojet* nozzle orifice — ($0.50 per cutting hour)
- extra power — ($0.50 per cutting hour)
- additional nozzles
- cutting fluid loss

Cycle Time

- job setup
- tool change
- nozzle adjustment

These costs are readily identifiable and measurable for a typical *flojet* operation. Additional costs are incurred during initial system acquisition and start-up (engineering, staff training, facility modification, etc.). Indirect costs for process engineering, maintenance, etc. are also incurred.

Cost Model, Economic Factors, and Analysis

The cost model and analysis approach used to evaluate the *flojet* system is done in three steps:

- First, calculate the required economic factors: i) Tool cost per life, ii) machine burden rate ($/minute), and iii) tool change time per life. The three machine burden rates are for a typical application using the BASE (or AS-IS), STANDARD FLOJET, and UNATTENDED FLOJET machining strategies.

- Second, determine the "best" cutting speed and tool life setting using the laboratory tool life data and economic factors. These settings are determined for each workpiece material (4340 steel, 17-4 PH steel, Inconel 718, titanium), and cutting tool (carbide, ceramic, or CBN) combination.

- Third, analyze a typical week's production of a part to determine i) cost per part, ii) parts per week, and iii) tool usage and net savings for STANDARD FLOJET vs. BASE and UNATTENDED FLOJET vs. BASE.

Step 1: Economic Factors

The economic factors are summarized in Table 6.

- Item 1 shows the machine burden rates for the BASE ($70.00 per hour), STANDARD FLOJET ($90.00 per hour), and UNATTENDED FLOJET ($60.00 per hour) strategies.

- Item 2 shows the tooling edge cost ($/life). The costs to be used are $1.50 per life (carbide), $85.00 per life (CBN), and $11.00 per life (ceramic).

- Item 3 shows the tool change time and cost for the three strategies.

- Item 4 shows the Tool/Machine Cost Ratios (T/M Ratio) for the various strategies and tool materials.

The T/M ratio is utilized with the tool life data to determine the "best" setting for cutting speed. Small T/M ratios favor high cutting speed and short tool life. Large T/M ratios favor slower cutting speeds resulting in longer tool life.

The detail calculations for the machine burden rates are shown in Table 7. This table serves as a framework to calculate machine burden rates for other applications. Typical values were used for the base machine cost, labor rates, and machine utilization factors. Note that the machine utilization factors were expressed as a percentage of the available productive hours planned for the equipment. Key to the analysis are the assumptions made for:

- Reduced chip removal downtime (8% to 0%) with ***flojet***.

- Increased setup time for STANDARD FLOJET (8% vs. 6%) and UNATTENDED FLOJET (12% vs. 6%).

- A ***flojet*** purchase price of $60,000 with $8,400 tooling (STANDARD FLOJET) and $14,000 tooling (UNATTENDED FLOJET).

- Additional capital costs for UNATTENDED FLOJET of $75,000 for part handling equipment, sensors, tool changing, and additional fixtures.

- Additional ***flojet*** operating costs per cutting hour.

Table 6 — Primary Economic Factors for *flojet* Value Analysis

PRIMARY ECONOMIC FACTORS

1) Machine Tool	Base	FloJet	Unattend
Depreciation ($/Year)	$23,571	$33,831	$45,921
Labor ($/Year)	$27,042	$27,042	$31,980
Operating ($/Year)	$11,300	$18,590	$28,186
BASE	$61,913	$79,463	$106,087
O/H & Profit	$61,913	$79,463	$106,087
Total Cost/Year	**$123,826**	**$158,925**	**$212,173**
Productive Hours	1,768	1,768	3,536
Machine Cost ($/Hr)	$70	$90	$60
Machine Burden ($/min)	**$1.17**	**$1.50**	**$1.00**

2) Tooling	Carbide	CBN	Ceramic
Purchase ($/Insert)	$6.00	$85.00	$22.00
Regrind Cost ($/Insert)	$0.00	$0.00	$0.00
Number Edges	4	1	2
Edge Cost ($/Life)	**$1.50**	**$85.00**	**$11.00**

3) Tool Change	Base	FloJet	Unattend
Insert Replace (Min.)	1.50	1.50	0.50
Nozzle Adjust (Min.)	0.00	0.50	0.00
Downtime (Min.)	1.50	2.00	0.50
Tool Change Cost ($/Life)	**$1.75**	**$3.00**	**$0.50**

4) T/M Cost Ratios

	Base	FloJet	Unattend
Carbide	**2.8**	**3.0**	**2.0**
CBN	**74.3**	**58.7**	**85.5**
Ceramic	**10.9**	**9.3**	**11.5**

T/M Ratio = (Edge Cost + Tool Change Cost) / Machine Burden

Table 7 – Detail Calculations for Machine Burden Rates

Machine Burden Rate Calculation

		Base	Base w/FloJet	Unattended
Capital Equipment				
Base Machine Cost		$150,000	$150,000	$150,000
Tooling	5.0% Equipment	$7,500	$7,500	$7,500
FloJet Equipment			$60,000	$60,000
Additional End Effectors			$8,400	$14,000
Part Load/Unload Equipment				$75,000
Freight & Installation	5.0% Equipment	$7,500	$10,920	$14,950
	NET INVESTMENT	$165,000	$236,820	$321,450
Depreciation (years)		7	7	7
	Depreciation Cost/Year	$23,571	$33,831	$45,921
Machine Utilization				
Weeks/Year		52	52	52
Hours/Week		40	40	80
Non-Scheduled Idle		15%	15%	15%
	Productive Hours	1,768	1,768	3,536
Part Load/Unload		8%	8%	4%
Set-Up		6%	8%	12%
Non-Cutting (e.g., Tool Position)		12%	12%	12%
Inspection & Adjustment		5%	5%	2%
Chip Removal		8%	0%	0%
	Net Cutting Percentage	61%	67%	70%
	Cutting Hours per Year	1,078	1,185	2,475
Labor				
Direct Labor per Machine Hour		50%	50%	10%
Indirect Labor per Machine Hour		10%	10%	20%
Direct Labor ($/hr)	@ $18.00 / Hour	$9.00	$9.00	$1.80
Indirect Labor ($/hr)	@ $25.00 / Hour	$2.50	$2.50	$5.00
Labor Benefits	33%	$3.80	$3.80	$2.24
	Labor Cost/Machine Hour	$15.30	$15.30	$9.04
	Labor Cost/Year	$27,042	$27,042	$31,980
Operating Costs				
Maintence Costs	2.0% Equipment	$3,150	$4,518	$6,130
Base Tooling (Fixturing, Gauge, etc.)		$2,500	$2,500	$2,500
FloJet Nozzle Inserts			$1,000	$1,500
FloJet Orifice	$0.50 per Hour		$592	$1,238
Material Handling				$1,000
Materials & Supplies	1.5% Equipment	$2,363	$3,389	$4,598
CO2 Usage	$1.50 per Hour		$1,777	$3,713
FloJet Filters	$0.50 per Hour		$592	$1,238
Base Power & Utilities		$2,500	$2,500	$3,500
- 50 Hp FloJet	$0.50 per Hour		$592	$1,238
Taxes & Insurance	0.5% Equipment	$788	$1,130	$1,533
	Operating Cost/Year	$11,300	$18,590	$28,186
Totals				
	BASE Cost/Year	$61,913	$79,463	$106,087
Overhead & Profit	100%	$61,913	$79,463	$106,087
	TOTAL Cost/Year	$123,826	$158,925	$212,173
	BURDEN RATE ($/HR)	$70.04	$89.89	$60.00
	($/min)	$1.17	$1.50	$1.00

Step 2: "Best" Settings

The determination of the "best" cutting speed with respect to machining economics is often based on minimizing the Unit Cost. The Unit Cost is the cost to machine a unit volume of material (a cubic inch, a hole, etc.), and is the sum of the machine time cost and tool usage cost.

$$UnitCost(\$/inch^3) = \frac{MachineBurden(\$/minute)}{MetalRemovalRate(inch^3/minute)} + \frac{ToolCost(\$/Life)}{ToolLife(inch^3/Life)}$$

The T/M Ratio is used is utilized in the standard analysis to determine the cutting speed which minimizes the Unit Cost. This cutting speed and the resultant tool life is considered the "best" setting for purposes of this analysis. Table 8 provides the "best" settings for the work material, cutting tool, and machining strategy combinations. As is common with today's economic environment, higher speeds, and lower tool life is recommended in most cases.

Step 3: Weekly Part Analysis

The analysis brings all of the above economic factors together by estimating the economics of a typical week's production using each of the three strategies (BASE, STANDARD FLOJET, UNATTENDED FLOJET). A typical part was identified as one in which a volume of 10 cubic inches of material was machined away. For each strategy, three cutting speeds (low, high and "best") were identified. For each of these conditions the following statistics were calculated:

- Cycle time per part
- Tool life usage
- Parts per week
- Tools per week
- Costs per Week
- Cost per part

Tables 9 through 16 show these calculations for the various work material and tool combinations.

Table 8 — "Best" Cutting Speeds and Tool Life for Different Strategies

Summary of "Best" Cutting Speeds

Material	Tool	Strategy	Cutting Speed		Tool Life
4340 Steel	Carbide	BASE	945 fpm		6 minutes
	Grade 415	STANDARD	1,278 fpm		6 minutes
		UNATTENDED	1,475 fpm		4 minutes
17-4 PH Steel	Carbide	BASE	735 fpm		7 minutes
	Grade 415	STANDARD	672 fpm		12 minutes
		UNATTENDED	729 fpm		8 minutes
Ti-6Al-4V	Carbide	BASE	254 fpm		13 minutes
	Grade H13A	STANDARD	367 fpm		9 minutes
		UNATTENDED	408 fpm		6 minutes
Inconel 718	Carbide	BASE	120 fpm		6 minutes
	Grade H13A	STANDARD	154 fpm		7 minutes
		UNATTENDED	175 fpm		5 minutes
Inconel 718	Ceramic	BASE	1,000 fpm	*	5 minutes
	Grade WG-300	STANDARD	1,000 fpm	*	2 minutes
		UNATTENDED	1,000 fpm	*	2 minutes
Inconel 718	CBN	BASE	461 fpm		5 minutes
	Grade 20	STANDARD	200 fpm	!	15 minutes
		UNATTENDED	135 fpm	!	24 minutes
M-50 Steel	Ceramic	BASE	237 fpm		22 minutes
	Grade WG-300	STANDARD	232 fpm		22 minutes
		UNATTENDED	218 fpm		27 minutes
M-50 Steel	CBN	BASE	180 fpm	!	75 minutes
	Grade 20	STANDARD	180 fpm	!	50 minutes
		UNATTENDED	180 fpm	!	50 minutes

Note: * Indicates Maximum Tested Speed
! Indicates Projected Tool Life

Table 9 — Weekly Cost Analysis for 4340 Steel with Carbide

Cost Comparison

Material: 4340 Steel, 320-340, BHN
Tool: CNMA-432, Grade 415

Volume/Part: 10 Cu.In.
Feed: 0.005 ipr

	Base			Base w/ FloJet			Unattended		
	Low	High	Best	Low	High	Best	Low	High	Best
SETTINGS									
Speed (fpm)	500	1000	945	500	1000	1278	500	1000	1475
Life (Min)	51	5	6	79	11	6	79	11	4
Rate (Cu.In./Min)	3.0	6.0	5.7	3.0	6.0	7.7	3.0	6.0	8.9
Burden ($/Minute)	$1.17	$1.17	$1.17	$1.50	$1.50	$1.50	$1.00	$1.00	$1.00
Edge Cost ($/Life)	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50
TIME									
Cut Time/Part	3.3 min.	1.7 min.	1.8 min.	3.3 min.	1.7 min.	1.3 min.	3.3 min.	1.7 min.	1.1 min.
Tool Life/Part	7%	33%	28%	4%	15%	24%	4%	15%	31%
Tool Change/Part	0.1 min.	0.5 min.	0.4 min.	0.1 min.	0.3 min.	0.5 min.	0.0 min.	0.1 min.	0.2 min.
Gross Time/Week	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	4,080 min.	4,080 min.	4,080 min.
Cutting/Week	1,209 min.	957 min.	1,008 min.	1,333 min.	1,157 min.	1,002 min.	2,838 min.	2,732 min.	2,516 min.
Tool Change/Week	36 min.	287 min.	236 min.	34 min.	210 min.	364 min.	18 min.	124 min.	340 min.
Other Non-Cut/Week	796 min.	796 min.	796 min.	673 min.	673 min.	673 min.	1,224 min.	1,224 min.	1,224 min.
OUTPUT									
Parts/Week	363	574	572	400	694	769	851	1,639	2,227
Tool Edges/Week	24	191	158	17	105	182	36	248	680
COSTS									
Cutting/Week	$1,411	$1,117	$1,177	$1,997	$1,733	$1,502	$2,838	$2,732	$2,516
Tool Edges/Week	$36	$287	$236	$25	$158	$273	$54	$373	$1,020
Tool Change/Week	$42	$335	$276	$51	$315	$546	$18	$124	$340
Other Non-Cut/Week	$929	$929	$929	$1,009	$1,009	$1,009	$1,224	$1,224	$1,224
Total/Week	$2,417	$2,668	$2,618	$3,082	$3,214	$3,330	$4,134	$4,453	$5,100
Total/Part	$6.66	$4.65	$4.58	$7.71	$4.63	$4.33	$4.86	$2.72	$2.29

Table 10 — Weekly Cost Analysis for 17-4 PH Steel with Carbide

Cost Comparison

Material: 17-4 PH Steel
Tool: CNMA-432 Grade 415

Volume/Part: 10 Cu.In.
Feed: 0.008 ipr

	Base			Base w/ FloJet			Unattended		
	Low	High	Best	Low	High	Best	Low	High	Best
SETTINGS									
Speed (fpm)	500	800	735	500	800	672	500	800	729
Life (Min)	25	5	7	52	5	12	52	5	8
Rate (Cu.In./Min)	4.8	7.7	7.1	4.8	7.7	6.5	4.8	7.7	7.0
Burden ($/Minute)	$1.17	$1.17	$1.17	$1.50	$1.50	$1.50	$1.00	$1.00	$1.00
Edge Cost ($/Life)	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50
TIME									
Cut Time/Part	2.1 min.	1.3 min.	1.4 min.	2.1 min.	1.3 min.	1.6 min.	2.1 min.	1.3 min.	1.4 min.
Tool Life/Part	8%	27%	21%	4%	27%	13%	4%	27%	18%
Tool Change/Part	0.1 min.	0.4 min.	0.3 min.	0.1 min.	0.5 min.	0.3 min.	0.0 min.	0.1 min.	0.1 min.
Gross Time/Week	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	4,080 min.	4,080 min.	4,080 min.
Cutting/Week	1,174 min.	953 min.	1,017 min.	1,316 min.	971 min.	1,170 min.	2,829 min.	2,592 min.	2,688 min.
Tool Change/Week	70 min.	292 min.	228 min.	51 min.	396 min.	197 min.	27 min.	264 min.	168 min.
Other Non-Cut/Week	796 min.	796 min.	796 min.	673 min.	673 min.	673 min.	1,224 min.	1,224 min.	1,224 min.
OUTPUT									
Parts/Week	564	732	717	632	745	755	1,358	1,990	1,881
Tool Edges/Week	47	194	152	25	198	98	54	529	336
COSTS									
Cutting/Week	$1,370	$1,112	$1,187	$1,972	$1,454	$1,753	$2,829	$2,592	$2,688
Tool Edges/Week	$70	$292	$228	$38	$297	$147	$82	$793	$504
Tool Change/Week	$82	$340	$266	$76	$594	$295	$27	$264	$168
Other Non-Cut/Week	$929	$929	$929	$1,009	$1,009	$1,009	$1,224	$1,224	$1,224
Total/Week	$2,452	$2,673	$2,609	$3,094	$3,353	$3,204	$4,162	$4,874	$4,584
Total/Part	$4.35	$3.65	$3.64	$4.90	$4.50	$4.24	$3.07	$2.45	$2.44

Table 11 — Weekly Cost Analysis for Titanium 6-4 with Carbide

Cost Comparison

Material: Ti-6Al-4V
Tool: CNMA-432, Grade H13A

Volume/Part: 10 Cu.In.
Feed: 0.006 ipr

	Base			Base w/ FloJet			Unattended		
	Low	High	Best	Low	High	Best	Low	High	Best
SETTINGS									
Speed (fpm)	175	300	254	175	300	367	175	300	408
Life (Min)	101	5	13	149	19	9	149	19	6
Rate (Cu.In./Min)	1.3	2.2	1.8	1.3	2.2	2.6	1.3	2.2	2.9
Burden ($/Minute)	$1.17	$1.17	$1.17	$1.50	$1.50	$1.50	$1.00	$1.00	$1.00
Edge Cost ($/Life)	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50
TIME									
Cut Time/Part	7.9 min.	4.6 min.	5.5 min.	7.9 min.	4.6 min.	3.8 min.	7.9 min.	4.6 min.	3.4 min.
Tool Life/Part	8%	93%	43%	5%	24%	44%	5%	24%	60%
Tool Change/Part	0.1 min.	1.4 min.	0.6 min.	0.1 min.	0.5 min.	0.9 min.	0.0 min.	0.1 min.	0.3 min.
Gross Time/Week	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	4,080 min.	4,080 min.	4,080 min.
Cutting/Week	1,226 min.	957 min.	1,113 min.	1,349 min.	1,237 min.	1,109 min.	2,846 min.	2,783 min.	2,626 min.
Tool Change/Week	18 min.	287 min.	131 min.	18 min.	130 min.	258 min.	10 min.	73 min.	230 min.
Other Non-Cut/Week	796 min.	796 min.	796 min.	673 min.	673 min.	673 min.	1,224 min.	1,224 min.	1,224 min.
OUTPUT									
Parts/Week	154	207	204	170	267	293	359	601	771
Tool Edges/Week	12	191	88	9	65	129	19	146	461
COSTS									
Cutting/Week	$1,431	$1,117	$1,299	$2,021	$1,853	$1,661	$2,847	$2,783	$2,626
Tool Edges/Week	$18	$287	$131	$14	$98	$193	$29	$220	$691
Tool Change/Week	$21	$335	$153	$27	$195	$386	$10	$73	$230
Other Non-Cut/Week	$929	$929	$929	$1,009	$1,009	$1,009	$1,224	$1,224	$1,224
Total/Week	$2,399	$2,668	$2,513	$3,070	$3,154	$3,250	$4,109	$4,300	$4,771
Total/Part	$15.53	$12.91	$12.35	$18.06	$11.81	$11.09	$11.46	$7.15	$6.19

Table 12 — Weekly Cost Analysis for Inconel 718 with Carbide

Cost Comparison

Material: Inconel 718
Tool: CNMA-432, Grade H13A

Volume/Part: 10 Cu.In.
Feed: 0.004 ipr

	Base			Base w/ FloJet			Unattended		
	Low	High	Best	Low	High	Best	Low	High	Best
SETTINGS									
Speed (fpm)	70	130	120	70	130	154	70	130	175
Life (Min)	29	4	6	86	12	7	86	12	5
Rate (Cu.In./Min)	0.3	0.6	0.6	0.3	0.6	0.7	0.3	0.6	0.8
Burden ($/Minute)	$1.17	$1.17	$1.17	$1.50	$1.50	$1.50	$1.00	$1.00	$1.00
Edge Cost ($/Life)	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50	$1.50
TIME									
Cut Time/Part	29.8 min.	16.0 min.	17.4 min.	29.8 min.	16.0 min.	13.5 min.	29.8 min.	16.0 min.	11.9 min.
Tool Life/Part	103%	401%	305%	35%	134%	202%	35%	134%	265%
Tool Change/Part	1.5 min.	6.0 min.	4.6 min.	0.7 min.	2.7 min.	4.0 min.	0.2 min.	0.7 min.	1.3 min.
Gross Time/Week	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	4,080 min.	4,080 min.	4,080 min.
Cutting/Week	1,183 min.	905 min.	985 min.	1,336 min.	1,172 min.	1,053 min.	2,839 min.	2,742 min.	2,570 min.
Tool Change/Week	61 min.	339 min.	259 min.	31 min.	195 min.	314 min.	17 min.	114 min.	286 min.
Other Non-Cut/Week	796 min.	796 min.	796 min.	673 min.	673 min.	673 min.	1,224 min.	1,224 min.	1,224 min.
OUTPUT									
Parts/Week	40	56	57	45	73	78	95	171	216
Tool Edges/Week	41	226	173	16	98	157	33	228	571
COSTS									
Cutting/Week	$1,381	$1,056	$1,150	$2,001	$1,755	$1,577	$2,840	$2,742	$2,571
Tool Edges/Week	$61	$339	$259	$23	$146	$236	$50	$343	$857
Tool Change/Week	$71	$396	$303	$47	$293	$471	$17	$114	$286
Other Non-Cut/Week	$929	$929	$929	$1,009	$1,009	$1,009	$1,224	$1,224	$1,224
Total/Week	$2,442	$2,721	$2,641	$3,080	$3,203	$3,292	$4,130	$4,423	$4,937
Total/Part	$61.44	$48.18	$46.53	$68.62	$43.81	$42.31	$43.29	$25.85	$22.87

Table 13 — Weekly Cost Analysis for Inconel 718 with Ceramic Tooling

Cost Comparison

Material: Inconel 718
Tool: CNGN-434-T1, Grade WG-300

Volume/Part: 10 Cu.In.
Feed: 0.004 ipr

	Base			Base w/ FloJet			Unattended		
	Low	High	Best	Low	High	Best	Low	High	Best
SETTINGS			(Max.)			(Max.)			(Max.)
Speed (fpm)	300	700	1000	300	700	1000	300	700	1000
Life (Min)	8	6	5	6	2	2	6	2	2
Rate (Cu.In./Min)	1.4	3.4	4.8	1.4	3.4	4.8	1.4	3.4	4.8
Burden ($/Minute)	$1.17	$1.17	$1.17	$1.50	$1.50	$1.50	$1.00	$1.00	$1.00
Edge Cost ($/Life)	$11.00	$11.00	$11.00	$11.00	$11.00	$11.00	$11.00	$11.00	$11.00
TIME									
Cut Time/Part	6.9 min.	3.0 min.	2.1 min.	6.9 min.	3.0 min.	2.1 min.	6.9 min.	3.0 min.	2.1 min.
Tool Life/Part	87%	50%	42%	116%	124%	130%	116%	149%	129%
Tool Change/Part	1.3 min.	0.7 min.	0.6 min.	2.3 min.	2.5 min.	2.6 min.	0.6 min.	0.7 min.	0.6 min.
Gross Time/Week	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	4,080 min.	4,080 min.	4,080 min.
Cutting/Week	1,048 min.	996 min.	957 min.	1,025 min.	746 min.	607 min.	2,636 min.	2,285 min.	2,179 min.
Tool Change/Week	196 min.	249 min.	287 min.	342 min.	621 min.	759 min.	220 min.	571 min.	677 min.
Other Non-Cut/Week	796 min.	796 min.	796 min.	673 min.	673 min.	673 min.	1,224 min.	1,224 min.	1,224 min.
OUTPUT									
Parts/Week	151	334	459	148	250	292	380	768	1,046
Tool Edges/Week	131	166	191	171	311	380	439	1,142	1,354
COSTS									
Cutting/Week	$1,223	$1,162	$1,117	$1,536	$1,117	$910	$2,636	$2,285	$2,179
Tool Edges/Week	$1,441	$1,825	$2,106	$1,879	$3,417	$4,176	$4,833	$12,566	$14,889
Tool Change/Week	$229	$291	$335	$512	$931	$1,138	$220	$571	$677
Other Non-Cut/Week	$929	$929	$929	$1,009	$1,009	$1,009	$1,224	$1,224	$1,224
Total/Week	$3,822	$4,206	$4,487	$4,936	$6,473	$7,233	$8,913	$16,647	$18,969
Total/Part	$25.33	$12.58	$9.77	$33.44	$25.84	$24.80	$23.48	$21.68	$18.13

Table 14 — Weekly Cost Analysis for Inconel 718 with CBN Tooling

Cost Comparison

Material: Inconel 718
Tool: CNMA-432-L1, Grade CBN-20

Volume/Part: 10 Cu.In.
Feed: 0.004 ipr

	Base			Base w/ FloJet			Unattended		
	Low	High	Best	Low	High	Best	Low	High	Best
SETTINGS						(Approx.)			(Projected)
Speed (fpm)	300	700	461	300	700	200	300	700	135
Life (Min)	8	3	5	9	3	15	9	3	24
Rate (Cu.In./Min)	1.4	3.4	2.2	1.4	3.4	1.0	1.4	3.4	0.6
Burden ($/Minute)	$1.17	$1.17	$1.17	$1.50	$1.50	$1.50	$1.00	$1.00	$1.00
Edge Cost ($/Life)	$85.00	$85.00	$85.00	$85.00	$85.00	$85.00	$85.00	$85.00	$85.00
TIME									
Cut Time/Part	6.9 min.	3.0 min.	4.5 min.	6.9 min.	3.0 min.	10.4 min.	6.9 min.	3.0 min.	15.4 min.
Tool Life/Part	87%	99%	90%	80%	99%	69%	81%	99%	64%
Tool Change/Part	1.3 min.	1.5 min.	1.4 min.	1.6 min.	2.0 min.	1.4 min.	0.4 min.	0.5 min.	0.3 min.
Gross Time/Week	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	4,080 min.	4,080 min.	4,080 min.
Cutting/Week	1,048 min.	830 min.	957 min.	1,111 min.	820 min.	1,206 min.	2,699 min.	2,448 min.	2,798 min.
Tool Change/Week	196 min.	415 min.	287 min.	255 min.	547 min.	161 min.	157 min.	408 min.	58 min.
Other Non-Cut/Week	796 min.	796 min.	796 min.	673 min.	673 min.	673 min.	1,224 min.	1,224 min.	1,224 min.
OUTPUT									
Parts/Week	151	279	212	160	276	116	389	823	181
Tool Edges/Week	131	277	191	128	273	80	314	816	117
COSTS									
Cutting/Week	$1,223	$968	$1,117	$1,665	$1,229	$1,807	$2,699	$2,448	$2,798
Tool Edges/Week	$11,134	$23,505	$16,273	$10,858	$23,236	$6,834	$26,677	$69,360	$9,909
Tool Change/Week	$229	$484	$335	$383	$819	$241	$157	$408	$58
Other Non-Cut/Week	$929	$929	$929	$1,009	$1,009	$1,009	$1,224	$1,224	$1,224
Total/Week	$13,515	$25,887	$18,654	$13,914	$26,292	$9,890	$30,757	$73,440	$13,989
Total/Part	$89.57	$92.87	$88.07	$86.95	$95.42	$85.43	$79.14	$89.29	$77.16

Table 15 — Weekly Cost Analysis for M-50 Steel with Ceramic Tooling

Cost Comparison

Material: M-50
Tool: CNGN-434-T1 Grade WG-300

Volume/Part: 10 Cu.In.
Feed: 0.004 ipr

	Base			Base w/ FloJet			Unattended		
	Low	High	Best	Low	High	Best	Low	High	Best
SETTINGS									
Speed (fpm)	200	350	237	200	350	232	200	350	218
Life (Min)	36	7	22	36	6	22	36	6	27
Rate (Cu.In./Min)	1.0	1.7	1.1	1.0	1.7	1.1	1.0	1.7	1.0
Burden ($/Minute)	$1.17	$1.17	$1.17	$1.50	$1.50	$1.50	$1.00	$1.00	$1.00
Edge Cost ($/Life)	$11.00	$11.00	$11.00	$11.00	$11.00	$11.00	$11.00	$11.00	$11.00
TIME									
Cut Time/Part	10.4 min.	6.0 min.	8.8 min.	10.4 min.	6.0 min.	9.0 min.	10.4 min.	6.0 min.	9.6 min.
Tool Life/Part	29%	85%	40%	29%	99%	41%	29%	99%	35%
Tool Change/Part	0.4 min.	1.3 min.	0.6 min.	0.6 min.	2.0 min.	0.8 min.	0.1 min.	0.5 min.	0.2 min.
Gross Time/Week	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	4,080 min.	4,080 min.	4,080 min.
Cutting/Week	1,195 min.	1,025 min.	1,165 min.	1,295 min.	1,025 min.	1,253 min.	2,817 min.	2,636 min.	2,804 min.
Tool Change/Week	50 min.	220 min.	79 min.	72 min.	342 min.	114 min.	39 min.	220 min.	52 min.
Other Non-Cut/Week	796 min.	796 min.	796 min.	673 min.	673 min.	673 min.	1,224 min.	1,224 min.	1,224 min.
OUTPUT									
Parts/Week	115	172	133	124	172	140	270	443	293
Tool Edges/Week	33	146	53	36	171	57	78	439	104
COSTS									
Cutting/Week	$1,394	$1,196	$1,360	$1,940	$1,536	$1,877	$2,817	$2,636	$2,804
Tool Edges/Week	$365	$1,610	$582	$396	$1,879	$626	$861	$4,833	$1,142
Tool Change/Week	$58	$256	$93	$108	$512	$171	$39	$220	$52
Other Non-Cut/Week	$929	$929	$929	$1,009	$1,009	$1,009	$1,224	$1,224	$1,224
Total/Week	$2,746	$3,992	$2,964	$3,452	$4,936	$3,683	$4,941	$8,913	$5,223
Total/Part	$23.95	$23.18	$22.36	$27.77	$28.66	$26.39	$18.27	$20.13	$17.80

Table 16 — Weekly Cost Analysis for M-50 Steel with CBN Tooling

Cost Comparison

Material: M-50 Steel (61 Rc)
Tool: CNMA-432-L1, Grade CBN-20

Volume/Part: 10 Cu.In.
Feed: 0.004 ipr

	Base			Base w/ FloJet			Unattended		
	Low	High	Best	Low	High	Best	Low	High	Best
SETTINGS			(Projected)			(Projected)			(Projected)
Speed (fpm)	200	300	180	200	300	180	200	300	180
Life (Min)	43	5	75	34	7	50	34	7	50
Rate (Cu.In./Min)	1.0	1.4	0.9	1.0	1.4	0.9	1.0	1.4	0.9
Burden ($/Minute)	$1.17	$1.17	$1.17	$1.50	$1.50	$1.50	$1.00	$1.00	$1.00
Edge Cost ($/Life)	$85.00	$85.00	$85.00	$85.00	$85.00	$85.00	$85.00	$85.00	$85.00
TIME									
Cut Time/Part	10.4 min.	6.9 min.	11.6 min.	10.4 min.	6.9 min.	11.6 min.	10.4 min.	6.9 min.	11.6 min.
Tool Life/Part	24%	139%	15%	31%	99%	23%	31%	99%	23%
Tool Change/Part	0.4 min.	2.1 min.	0.2 min.	0.6 min.	2.0 min.	0.5 min.	0.2 min.	0.5 min.	0.1 min.
Gross Time/Week	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	2,040 min.	4,080 min.	4,080 min.	4,080 min.
Cutting/Week	1,202 min.	957 min.	1,220 min.	1,291 min.	1,063 min.	1,314 min.	2,815 min.	2,666 min.	2,828 min.
Tool Change/Week	42 min.	287 min.	24 min.	76 min.	304 min.	53 min.	41 min.	190 min.	28 min.
Other Non-Cut/Week	796 min.	796 min.	796 min.	673 min.	673 min.	673 min.	1,224 min.	1,224 min.	1,224 min.
OUTPUT									
Parts/Week	115	138	105	124	153	114	270	384	244
Tool Edges/Week	28	191	16	38	152	26	83	381	57
COSTS									
Cutting/Week	$1,404	$1,117	$1,424	$1,934	$1,593	$1,969	$2,815	$2,666	$2,828
Tool Edges/Week	$2,377	$16,273	$1,383	$3,227	$12,909	$2,234	$7,037	$32,368	$4,807
Tool Change/Week	$49	$335	$28	$114	$455	$79	$41	$190	$28
Other Non-Cut/Week	$929	$929	$929	$1,009	$1,009	$1,009	$1,224	$1,224	$1,224
Total/Week	$4,758	$18,654	$3,764	$6,283	$15,965	$5,290	$11,117	$36,448	$8,887
Total/Part	$41.22	$135.33	$35.71	$50.70	$104.29	$46.59	$41.14	$94.96	$36.38

Results

Figures 4 to 9 show the cost per part and parts per week statistics for the three strategies. Note that Figures 4 to 7 are for carbide tooling datasets (4340 steel, 17-4 steel, titanium 6-4, and Inconel 718, respectively). Figure 8 is the Inconel 718 data with all three tooling materials (carbide, CBN, and ceramic). Figure 9 is the M-50 steel data with CBN and ceramic tooling. As can be seen, the UNATTENDED FLOJET strategy provides significant benefits (both part cost and production) over the other two strategies. The STANDARD FLOJET strategy provides a slight positive net savings over the BASE strategy and significant increases in production.

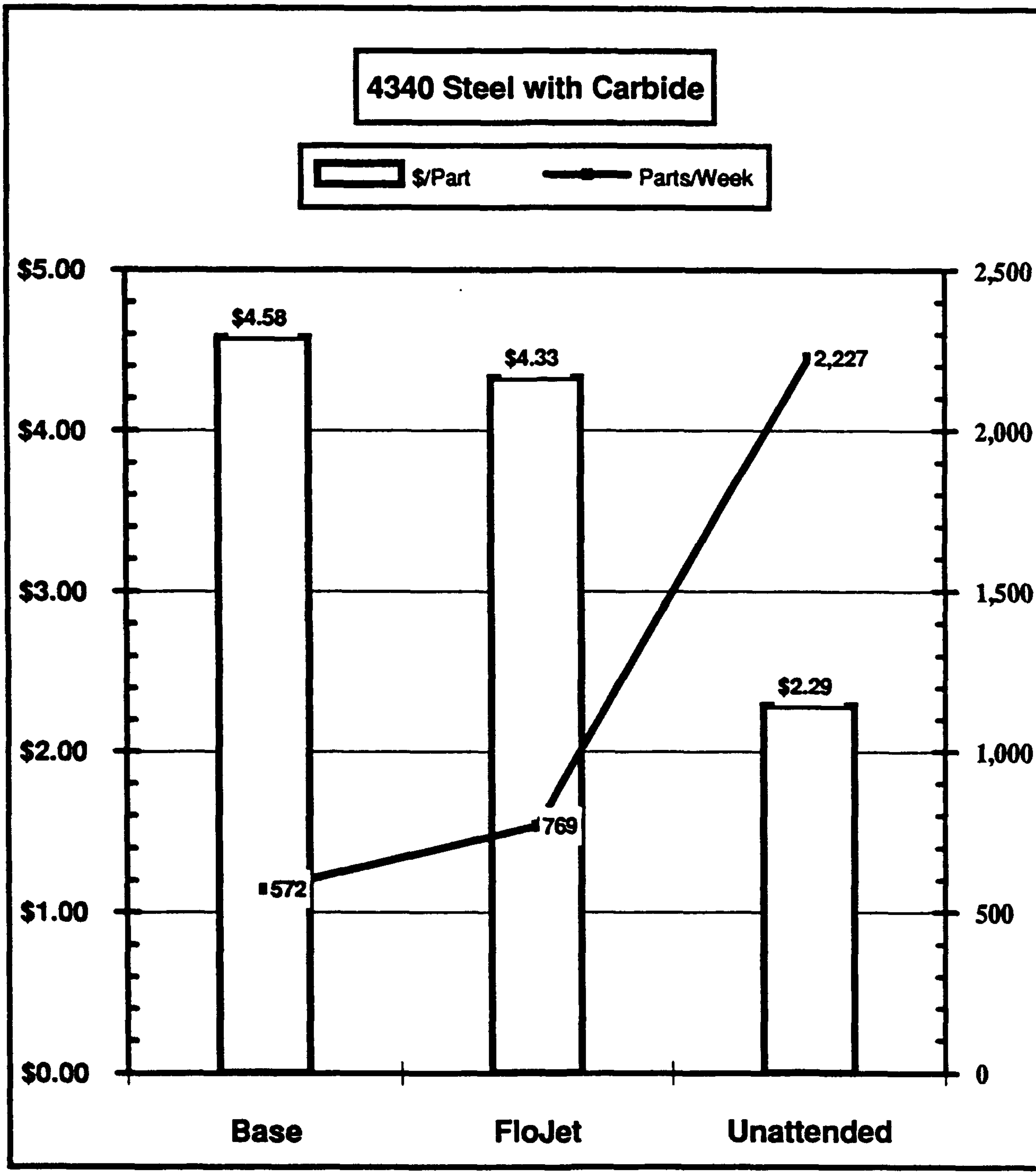


Figure 4 — Economic Data for 4340 Steel with Carbide Tooling

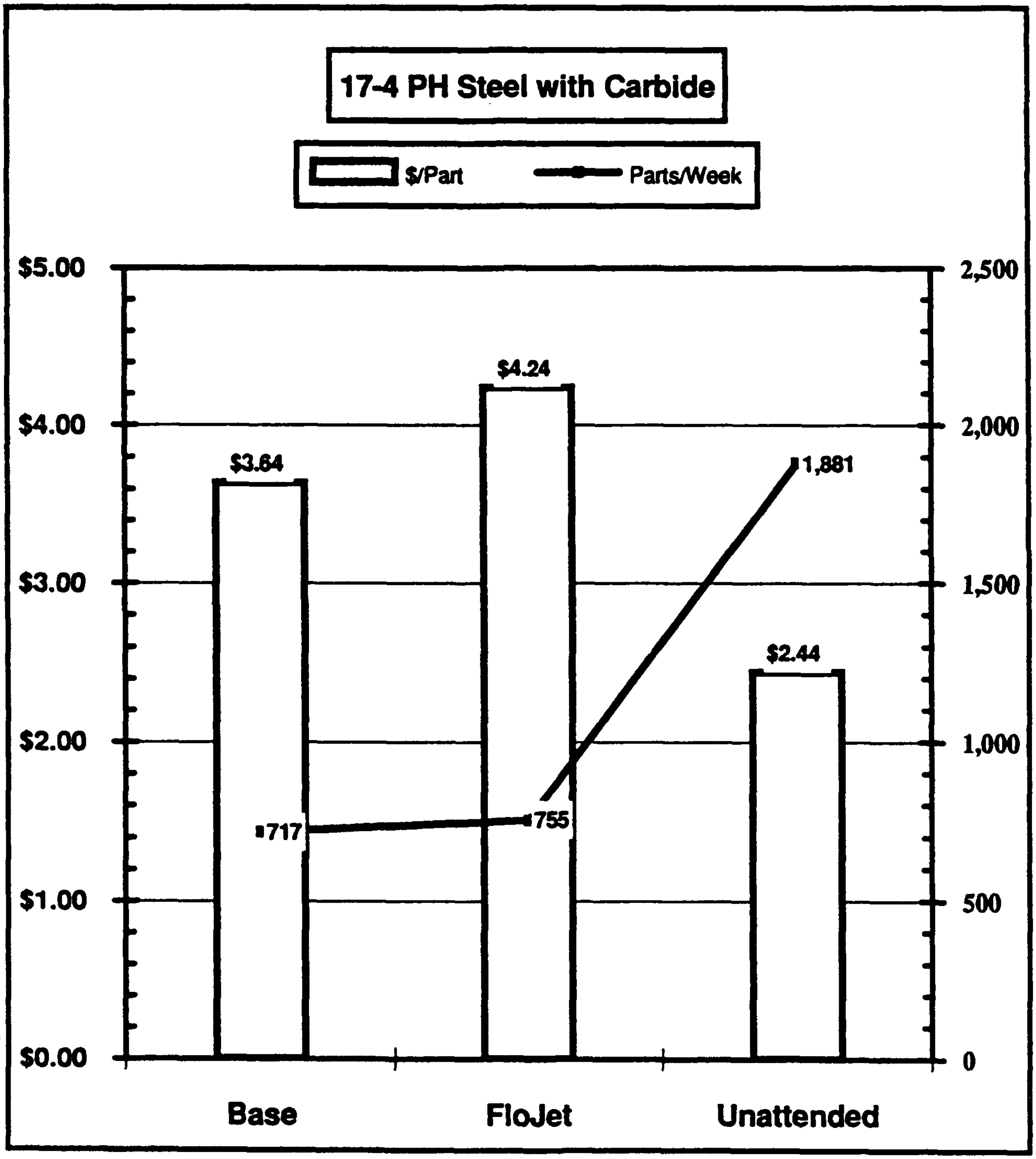


Figure 5 — Economic Data for 17-4 PH with Carbide Tooling

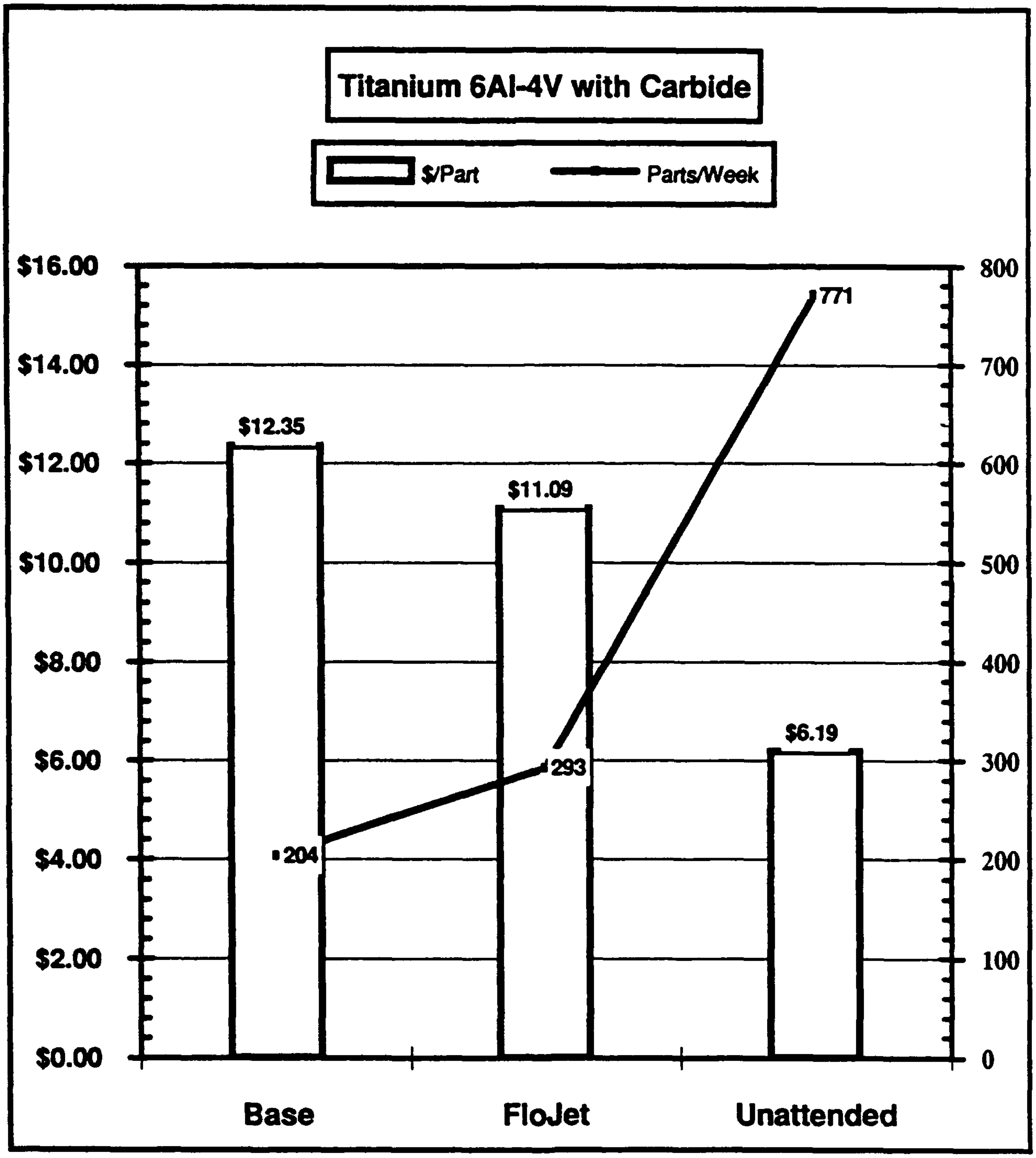


Figure 6 — Economic Data for Titanium 6-4 with Carbide Tooling

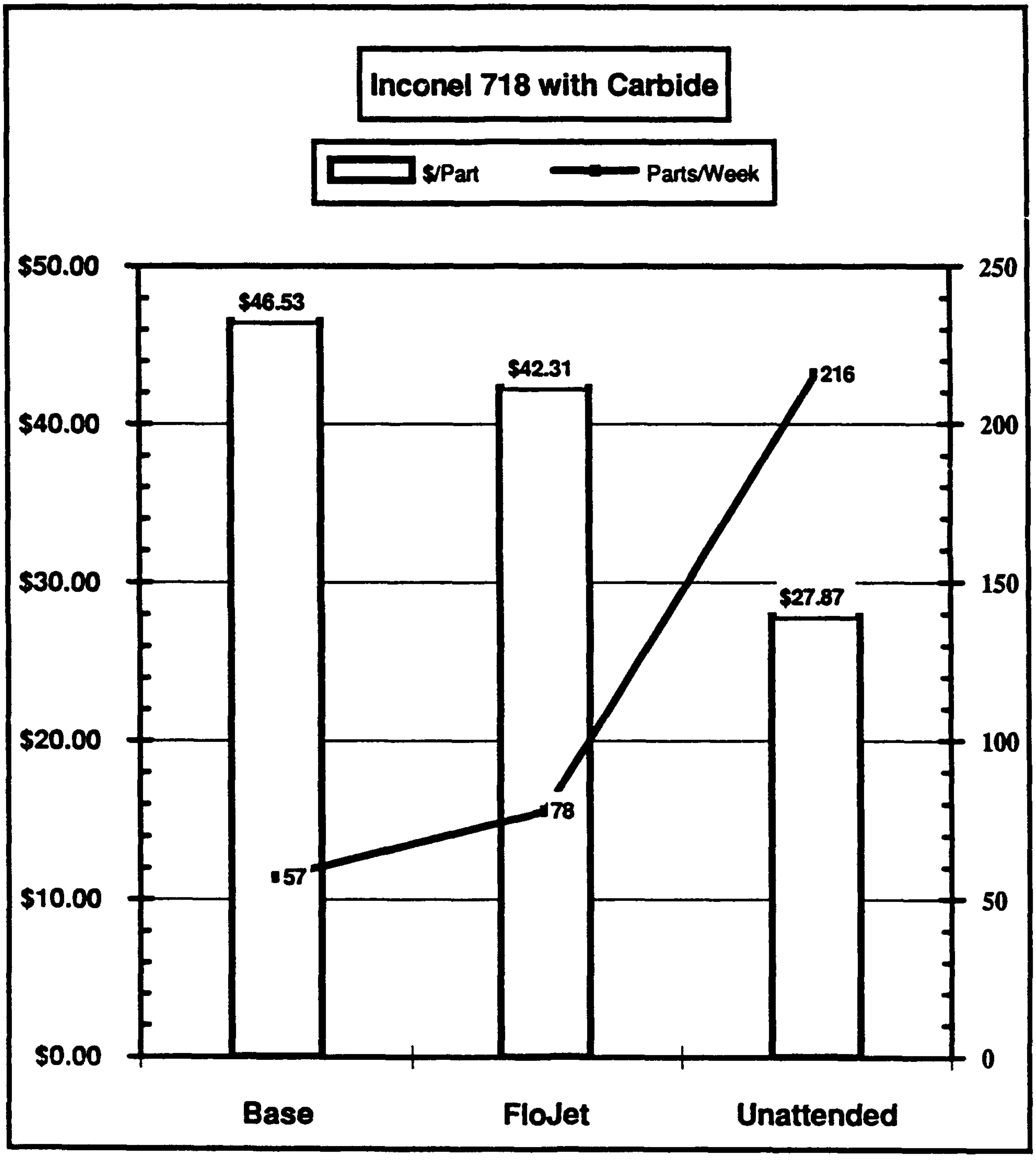


Figure 7 — Economic Data for Inconel 718 with Carbide Tooling

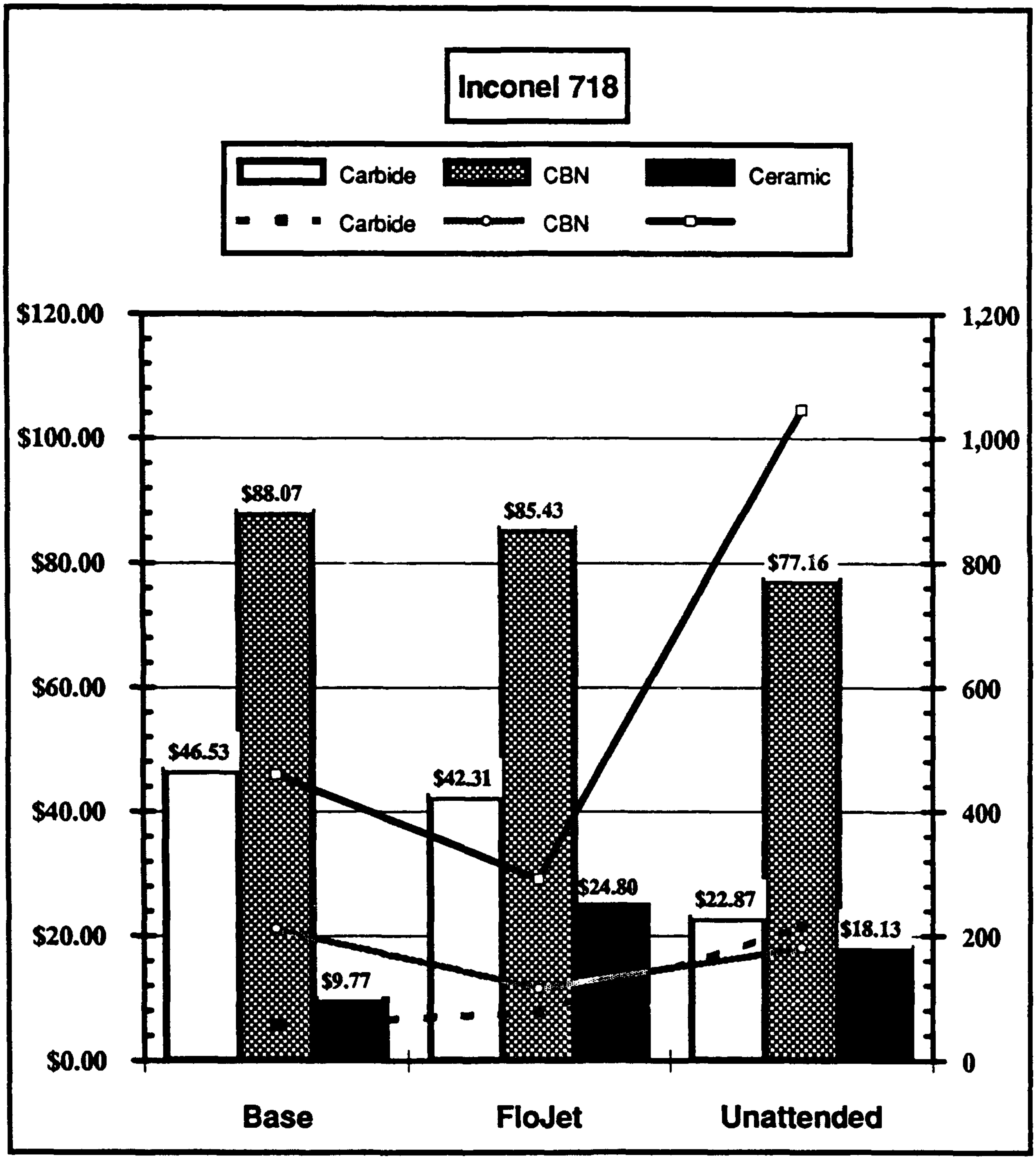


Figure 8 — Economic Data for Inconel 718 with Various Tooling

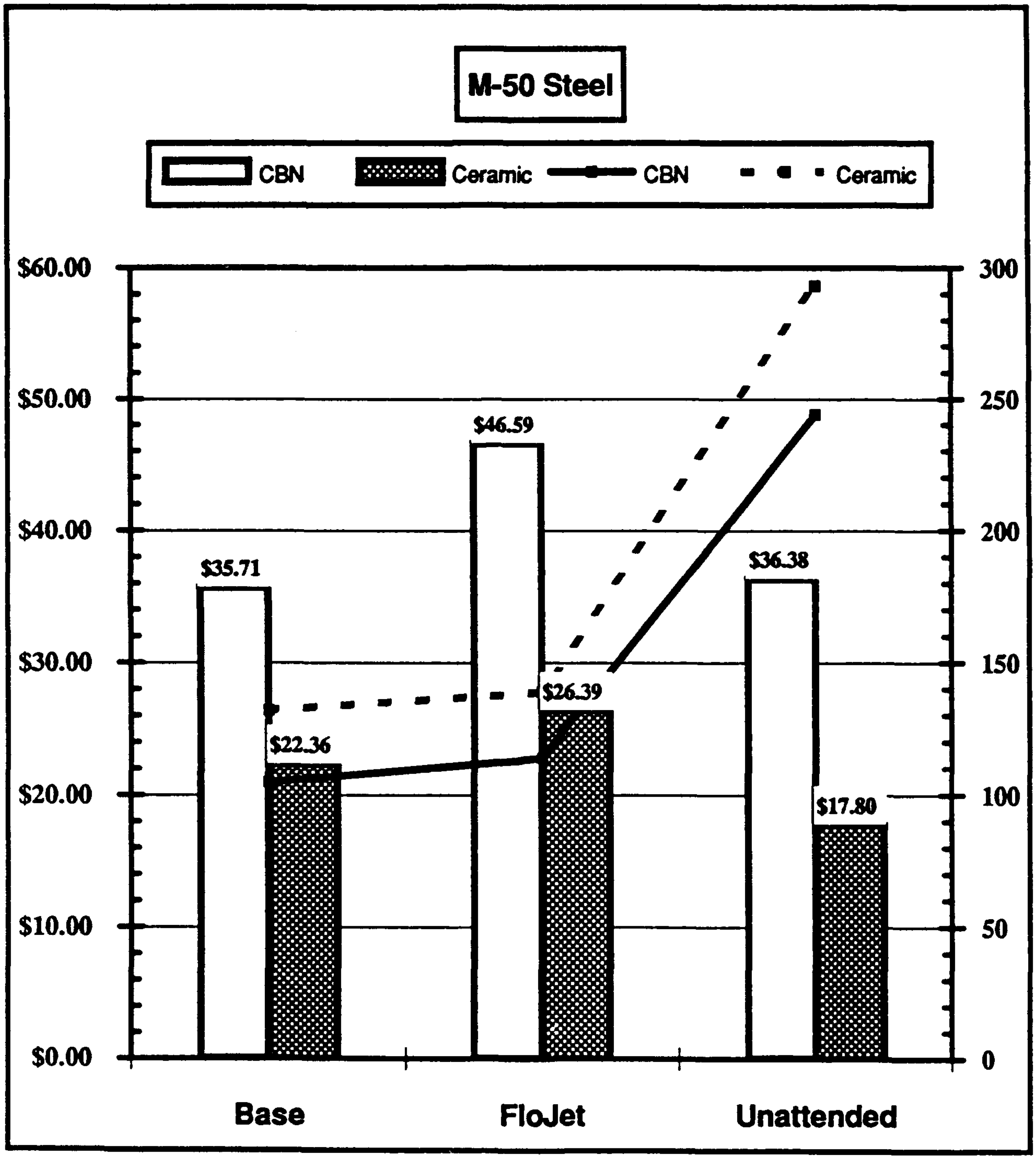


Figure 9 – Economic Data for M-50 Steel with Various Tooling

Conclusions

The conclusions drawn from this analysis can be summarized in several groups according to the dataset being analyzed.

Carbide Tooling Datasets

- The ***flojet*** system used in a STANDARD strategy provides nominal cost-per-part savings and increased production. The following summarizes the analysis:

Material	Cost Savings	Production
4340 Steel	5%	34%
17-4 PH Steel	-16%	5%
Titanium 6-4	10%	43%
Inconel 718	9%	37%

- The ***flojet*** system used in an UNATTENDED strategy provides significant cost-per-part savings and increased production. The following summarizes the analysis:

Material	Cost Savings	Production
4340 Steel	50%	289%
17-4 PH Steel	33%	162%
Titanium 6-4	50%	278%
Inconel 718	40%	279%

- Heat is carbide tooling's major tool life factor. The ***flojet*** system provides sufficient cooling to approximately double the tool life. With this performance, the ***flojet*** appears to be economically feasible.

M-50 Steel Dataset

- Ceramic tooling is recommended with M-50 steel. The hardness and strength of this material is the major tool life factor. Use of high temperatures with ceramic tooling appears to be beneficial due possibly to a softening of the material.

- The additional cooling provided by ***flojet*** is not beneficial. The STANDARD FLOJET strategy <u>increased</u> part costs since no tool life improvement is provided by ***flojet***. Flood coolant is recommended.

- Production slightly increased with ***flojet*** due to reduced downtime for chip removal. This additional time allowed more parts per week to be produced.

- The UNATTENDED FLOJET strategy is recommended. Part costs were reduced 20% and weekly production increased 122% (primarily due to two-shift operation).

Inconel 718 Dataset

- Ceramic tooling is recommended. The increased cost of CBN is not justified and carbide tooling did not have the tool life and cutting speed performance.

- Flood coolant is recommended over ***flojet*** for operator-assisted machining since the higher temperatures with ceramic tooling are beneficial. Part costs increased with ***flojet*** use.

- UNATTENDED machining is recommended only if ***flojet*** is not required for chip control purposes. Since ***flojet*** hurts the tool life performance, other chip control methods, if appropriate, would be preferred. Part costs increased 86% with UNATTENDED FLOJET.

General

The following points can be summarized from the economic value analysis:

- The ***flojet*** system appears to be economically feasible when it delivers the tangible benefits of longer tool life and higher cutting speeds. FLOJET GENERATES A POSITIVE SAVINGS.

- The intangible benefits of the ***flojet*** system depend upon the industrial context and may be sufficient to justify the investment risk.

- The use of CO_2 in the ***flojet*** system is insignificant in both a technical performance and cost sense.

- Very significant reductions in part costs and increases in production rate are achieved with unattended machining. If chip control is required to achieve unattended operation, then the ***flojet*** system can be confidently justified.

CONCLUSIONS

For materials similar to those in the test group, the *flojet* system can provide nearly universal chip control. Industrial feedback indicates that this is a significant benefit in its own right. The potential value of a system that provides manageable swarf is also underscored by an economic analysis that clearly indicates the value of unattended machining. Less tangible but no less important is the improved process consistency that is the prerequisite for unattended operations.

Improvements in tool life are also possible with *flojet* for some combinations of workpiece and tool material. The data suggest that in applications where tool life is predominantly temperature dependent, *flojet* can provide significant increases in tool life – approximately double when compared to flood cooling for the materials tested here. However, if the primary failure mechanism of the tool is abrasion or force, such as is often the case with very hard or tough materials, a tool life benefit due to *flojet* would not be expected. The *flojet* system would also be expected to have little effect on tool life for tool materials that are not temperature sensitive, such as the CBN tested here.

The data do not support a cryogenic effect on the tool or the chip due to the CO_2 stream. However, the tool life data – particularly the decrease in performance when using *flojet* for the inconel/ceramic test – do suggest that *flojet* provides better cooling than flood coolant application. This is probably due to the higher pressure and flowrates of the coolant stream forcing the fluid further into the cutting zone. The improved cooling is thus due to better application of a cool fluid, rather than a cryogenic effect. First, higher pressures and flowrates yield better fluid contact and improved heat transfer. Second, if the high pressure fluid stream provides better lubrication or lifts the chip and reduces the contact length between the chip and the rake face of the tool, less frictional heat will be generated. The force of the high-pressure coolant stream is probably also responsible for the chip breaking performance, rather than any cryogenic embrittlement of the material.

The data do not support the effects of improved surface finish, reduced cutting forces, or reduced horsepower for the materials and parameters in the test matrix. It should be noted that the surface finish of the soft materials looked significantly different comparing flood and *flojet* machining with the latter tending to produce a matte finish. Despite the visual differences, surface finish readings did not vary significantly.

The *flojet* system is economically feasible in some cases. Justification is based on increased tool life and productivity. The system may also be justified less tangibly through the benefit of reliably producing broken chips, resulting in improved process consistency and safety.

APPENDIX A

STATE-OF-THE-ART REPORT ON CHIP CONTROL

STATE-OF-THE-ART REPORT ON CHIP CONTROL

Introduction

The production of chips is the natural result of the metalcutting process. Chip formation, classification, and disposal have been studied for more than a century. In many cases, the chips that are produced are little more than a controllable nuisance. However, there are a number of engineering work materials and machining operations that produce chips that are hazardous to the operator, the workpiece, or the machine tool.

In today's high speed machining situations, the production and disposal of chips need to be carefully controlled. Maximum utilization of CNC machine tools can be achieved only if the optimized machining parameters result in chips of a conveniently disposable shape. The variations in chip form depend upon many factors including the work material, machining parameters, tool geometry, type of machining operation, and perhaps the cutting fluid. Thus, for optimum metal removal rates, it is also necessary to use methods that do not permit objectional chips to be formed (1).

At the present time, there are many sources of information on chip control methods. A comprehensive survey of published literature on the subject of chip control and its characteristics was performed. This survey included the collecting, sorting, reviewing, and compiling the information available on the subject of chip control. Relationships between the theoretical principles of chip breaking and the commercially available methods or systems were made from this information.

Chip Breaking: Fundamentals and Practical Aspects

A general review of the fundamentals of chip formation and chip control mechanisms was made. The factors affecting chip control have been discussed and summarized from the literature that was reviewed. Many of these factors can only be estimated because of nonsteady-state effects that occur during the machining operation (2). However, chip formation can be somewhat controlled by the use of chip control-type inserts. There are two common types, the obstruction type and the groove type. Both of these types of chip control devices achieve chip flow which is directed away from the workpiece. The size of the chip is controlled by the design of the chip breaker working in conjunction with the correct machining conditions. The result of this combination should be chips of acceptable size and shape.

A comparison was made of newer chip control designs and their advantages compared with

previous or older designs. Modern designs consist of the cutting edge having a multidimensional rake face consisting of one or several grooves, bumps, dimples, or a combination of several of these designs. The expected effect of this complicated geometry is two-fold: first, the geometry of the chip is better defined and is less influenced by variations in workpiece material; second, the chip can withstand less deformation, thus is forced to break with greater reliability.

Another method of controlled chip flow is by the careful adjustment of the cutting conditions of the workpiece material being machined. This method may reduce the metal removal rate and have a negative influence on productivity. As a result, the most common and acceptable way to obtain a controlled chip condition is still with the aid of a chip breaker (3).

The optimum combination of chip groove design and cutting conditions could be determined by testing every groove design with every combination of cutting conditions on every material. This would be a very time-consuming and costly process and is not practical. Some of this type of testing has been performed, but to cover every application, much additional testing is needed (4).

Photographing chips and relating them to the machining conditions from which they were obtained is one method of recording chip breaking data. The different sizes and shapes of the chips reflect the variations in the machining conditions of speed, feed, and depth of cut. The presentation is usually done graphically and describes all levels of variables. The data shown in this manner is of considerable value in determining chip breaker design parameters for a variety of materials. This type of testing is a good but costly source of chip control information (5, 6).

All practical aspects of chip control, chip breaking, and the selection of chip breaking devices have been reviewed and investigated. Basic geometries and tool materials for chip breakers were considered and identified when reviewing the literature. A review of chip breaker design for both turning and boring was made using the available literature ranging from research journals to manufacturers' catalogs. Much of the material was reviewed and evaluated and the performance of different chip breaker designs was compared. The results of these comparisons and studies were discussed in detail, showing data of cost, effectiveness, and drawbacks of each chip breaker device presented (7-14).

In addition, there has been some research and development of alternative methods of chip breaking and chip control. Some of these alternative methods differ from the conventional methods of chip breaking in their basic concepts, while others are variations or combinations of conventional methods. There seems to be some promise for about three of these lesser known and infrequently used methods. These methods include: vibration methods (15, 16), relaxation

or interrupted feed (17-22), and high pressure coolant jet (23-27).

The Report

This report covers a study to determine the state-of-the-art of chip control in turning and boring. The study was completed by a literature search, review, and evaluation of all documents. The parameters or limiting factors of the search were:

- Any Chip Control Methods
- Limited to Turning and Boring Operations
- All Workpiece Materials
- The Subject of Chip Control Only

The search produced 199 selected documents for review and evaluation. This report summarizes the results of that review and evaluation to establish the state-of-the-art in chip control.

Summary

This literature search and review examined several different methods of chip control. The six main methods of control covered in this report are:

1. Tool Geometry (grooves, steps, dimples, etc.)
2. High pressure Coolant Application
3. Vibrating the Cutting Tool
4. Interrupting the Feed Rate
5. Alterations in the Workpiece Material Composition
6. Mechanical Chip Breakers

This report also has a chip breaking category called Other. In this category the report reviews literature that describes chip control by methods such as grooving the workpiece (28), adjustments of the machining parameters, "roller" breakers (29-30), etc. The Other category also contains documents with information about the sensing of the chip formation by monitoring acoustic emissions (31) and chip formation prediction by use of computer analysis programs (32).

Fifty-six percent of all the documents reviewed related to chip control by means of commercially available tool geometry (grooves, bumps, etc.) methods of control. High pressure coolant methods of control account for only 3.5% of all of the documents reviewed, while vibrating the cutting tool and interrupting the feed rate have approximately 10% each of the total. Altering the workpiece material composition accounted for 4.5% and mechanical breakers produced 5.5% of the total. This leaves approximately 11% of the total 199 documents in the category of Other.

All the documents reviewed contributed to establishing the state-of-the-art. However, some documents contain information prior to 1950. This report includes the evaluation of these documents prior to 1950. This report includes the evaluation of these documents as a means of presenting the "evolution process" or historical progress of chip control technology to its present state.

The category with the longest history was tool geometry. Tool geometry methods of chip control have been in use longer than any other techniques. The current state-of-the-art in chip control can be describes as follows:

Chip control remains as one of the most serious, unsolved problems in machining. When machining ductile materials, this problem can cause safety hazards to the operator, decreased tool life (chipping and breaking of the tool), surface finish damage, and reduced productivity.

Improvements in chip control methods are severely needed by the machining industry.

Tool geometry (groove type inserts) methods are still the most widely used chip control devices.

In recent years, very little improvement has been made in the technology of incorporating grooves, bumps, angles, and dimples in indexable inserts. Most manufacturers are supplying inserts with various modifications of grooves. The changes that have occurred are in the number, location, size, and type of obstructing grooves, dimples, or bumps used. These changes have helped to increase the overall effectiveness of the chip control inserts. Unique designs that meet the requirements of specific workpiece materials or applications have resulted from these changes. However, the same basic technology used in the mid-1960's is still in use today.

Research and testing have not produced any major changes. Little or no designs have been tested or evaluated other than those provided by the insert manufacturers. This category does not show a great deal of promise for more improvement without a radical new development or improvement in the technology. Over the years since this technology was introduced, the manufacturers have added bumps, moved grooves, changed angles, and modified the overall geometry in about as many effective combinations of these improvements as possible (1).

Some, but relatively little, progress has been made in the research and development of the category designated as Alternative methods of chip control. The three most promising methods are:

1. Vibroturning, Vibration of the Cutting Tool
2. Interrupted Feed, A Brief Pause in the Feed Rate
3. High Pressure Coolant Flow

Other alternative methods such as modifications to the chemical composition of the workpiece material, roller breakers, and grooving the workpiece will not be discussed. Although they may be of benefit in some applications, they are very limited in both use and effectiveness. The state-of-the-art renders these methods within this category to be too expensive for consideration or impractical for a cost-effective production application. The only obvious exception is the use of leaded or resulfurized steels for improved machinability. One of the improvements is usually better chip control as well as reduced tool wear.

Summary Discussion of Alternative Methods

1. Three promising alternative methods of chip control have been developed to a level of possible application.

2. Insufficient research or development effort has been devoted to cost-effective applications of the three most promising alternative methods of chip control.

3. Relatively little research and development activity is currently underway in these alternative methods.

4. Limited production use of these three methods has been attempted.

5. Limited production application information and data are available for the three most promising methods.

6. Aggressive research and testing of these three methods are needed to expand effective chip control beyond the current limitations of that available with tool geometry from indexable inserts.

State-of-the-Art for the Three Alternatives

Vibroturning

The vibration method is a mechanical means of using the natural tendency for vibration in machining. These natural vibrations along with other instabilities of the cutting process comprise

one means of breaking the chips. Research has been performed to determine if these vibrations, whether self-excited or induced, are sufficiently controllable and predictable to assist in chip breaking. The vibroturning method of chip control can be applied in turning and boring operations. If applied properly, and the machining conditions remain constant with little variation, vibroturning seems to be effective in chip control. It has not been applied in many production applications because of its present drawbacks. There are known problems that must be resolved before this method of chip control can have wide acceptance. Some of these problems are listed below.

1. Initial cost of tooling retrofit.

2. The wide variation of frequencies required to maintain an effective chip breaking condition. Similar to the tool geometry method of control, changing machining conditions affect the efficiency of this method. Some of the changing conditions can include: tool wear, variations in the hardness of the workpiece, changing the feeds and speeds to increase production or improve surface finish, and unexpected vibrations from external sources. Any of these changes can influence how effectively the vibroturning method works. The frequency of vibration must be altered to compensate for any changes. This creates the need for constant monitoring of the operation and some automatic compensating system to maintain the effective frequency.

3. Vibroturning systems can reduce tool life.

4. On finish cuts, vibroturning can improve surface finish.

5. The present vibroturning systems are large and cumbersome, restricting their application (33-44).

Interrupted Feed

Another method of chip control called "interrupted cutting" has been examined and found to be effective in a turning operation where the workpiece diameter is in excess of four inches. This method of chip control is also known as "relaxation cutting" or interrupted feed." Interrupted cutting was named for its two-phase feed cycle. The cycle is accomplished by the secondary and oscillatory motion of the cutting tool, first in the same direction as the primary feed and then reversing its motion while the primary feed continues in its normal direction. The secondary oscillating motion, first forward then reversed, combined with the continuous primary feed, achieves a relaxed or interrupted total feed.

The interrupted feed method of chip control can also be applied to most turning or boring operations. When properly applied, the method can achieve acceptable chip control with fewer problems than the vibroturning method. Interrupted feed does have its drawbacks, as listed below:

1. Initial cost of tooling retrofit.

2. Possible negative effect on tool life.

3. Possible degradation of the surface finish.

4. Possible increase in machining costs by increasing cycle time (45-49).

High Pressure Coolant

High pressure coolant, sometimes called liquid jet or hydraulic chip breaking, is a method by which long, unbroken chips are broken into acceptable chips by applying high pressure liquid to the cutting zone through an appropriately designed nozzle. In some applications, the liquid has been refrigerated. Liquid temperature, pressure, nozzle design, flow direction, and machining parameters have all been tested with a variety of workpiece materials. These test results showed that acceptable chip control can be achieved when machining materials with normally poor chip breaking characteristics. Nozzle design, flow pressure, flow direction and location, type of fluid, and other process parameters have been recommended for some workpiece materials. Effects of the process on the workpiece and the cutting tools are negligible, in that the surface hardness and finish of the workpiece do not show detrimental effects compared to normal machining practice. There is an indication of positive effects on tool wear, but insufficient test results with hydraulic chip breaking have been found in the literature to provide a conclusive comparison.

High pressure jet chip breaking reduces the tendency to develop a built-up edge when machining softer materials at low speeds. There are safety considerations associated with the process, such as toxic liquids and high liquid pressures resulting in high fluid velocity. At the present stage of development, research has shown that hydraulic chip breaking may be an efficient alternative method to traditional (insert geometry) ways of chip control. The process requires in-depth research of all its contributing elements.

High-pressure coolant is the last alternative method that will be discussed in this report. This method can be applied to most turning and boring operations, but with fewer drawbacks than the vibroturning or interrupted feed methods. Its biggest drawback is the initial cost of retrofitting

machine tools and replacing existing cutting tool holders. With the available technology, this initial cost is usually high.

When chip control is a major problem, this method is one of the most effective and requires the least amount of attention or adjustments. In addition, high-pressure coolant has shown a positive effect on tool life, surface finish, and productivity. Most of these benefits can be consistently achieved with little system adjustments regardless of the changing variables and machining conditions (23-27). The benefits derived from high-pressure coolant producing acceptable and consistent chip control are:

1. Increased productivity due to less downtime for chip removal by operator intervention.

2. Increase in the use of more unattended machining.

3. Increased tool life by reduction of wear.

4. Improvement in surface roughness resulting from better chip formation and elimination of the continuous chips scarring the machined surface.

5. Little or no system adjustments required.

The main drawback to using the high-pressure coolant method of chip control is the initial cost of pumping equipment and tool holders.

Final Summary of the State-of-the-Art in Chip Control

The problems resulting from long unbroken chips are well-known to the machining industry. There are certain combinations of machining conditions and workpiece materials which do not produce acceptable chip control. Long strings of continuous chips create safety risks, damage workpiece surface finish, and may cause damage to the cutting tool and even the machine tool. These undesirable conditions contribute to both reduced productivity and increased machining costs.

It is sometimes difficult to predict the level of chip control that will result in a specific machining situation. There are several factors that have an influence on this inability to predict chip control. The workpiece material, its chemical composition, microstructure, and hardness have the greatest influence. Other factors of tool geometry and machining parameters may also contribute to the presence or absence of chip control. There is usually some range of adjustment to control the

influence of cutting conditions and tool geometry.

The chip control insert is perhaps the best example of a positive effort to overcome the other influences that limit obtaining broken chips. Research must continue to explore insert geometries that have a wider range of effectiveness with regard to work materials and machining conditions. Activities both in the U.S. and internationally are currently addressing standard classification systems for chipbreaker inserts according to their relative performance characteristics in a specified machining application. These characteristics are, 1) the feed rate range over which an insert controls the chip most effectively, and 2) the magnitude of the cutting force arising from the interaction of an insert with the workpiece. With new chip breakers designed for broader ranges of application and the increased knowledge gained from research, greater predictability and reliability should be achievable.

Chip control is one of the last important obstacles impeding increased productivity and decreased machining costs on many alloys. Efforts in research and testing of systems or methods that will remove that obstacle are needed today. Present methods are not always adequate for today's demanding high-speed machining operations. These methods are often lacking in reliability and consistency for unattended operation within a changing environment. There are some methods that show potential in meeting the needs, but they have not been tested and applied to the extent where the machining industry can feel comfortable with investing the initial cost for their implementation.

If the machining industry is ever to have reliable and acceptable chip control, efforts must continue in the development and validation of methods that resolve the problems of high cost and reliability. In order for the industry to accept and apply these new methods, they must be proven reliable, consistent, and cost effective. This validation can only come from the collection of pertinent, accurate data which are widely disseminated to the machining industry.

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APPENDIX B

DATA FOR TOOL LIFE AND ECONOMIC ANALYSES

Tool Life Analysis

Dataset: Flood Coolant on 4340 Steel with Carbide Tooling

Test Parameters

Work Material:	4340 Steel, 320-340, BHN		
Operation:	Turning	**Cut Type:**	O.D. Roughing - FLOOD
Cutting Tool:	CNMA-432, Grade 415	**Cutting Fluid:**	Trim_Sol (20:1); Flood Application
Part Diameter:	6.00 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.005 ipr		
Life Units:	Minutes (**Original**)		
Life Criterion:	0.015" Uniform or 0.030" Local Wear		

Tool Life Data

Feed (ipt)	Speed (fpm) 450	600	700	800	900	
0.005	**68.0**	**27.0**	**16.0**	**11.5**	**7.1**	**Tool**
0.005	**73.0**	**33.0**		**12.2**		**Life**
0.005				**10.0**		**(Minutes)**

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.005	Estimated Life (Minutes) for Feed of 0.005	Desired Speed
10	824	106	**400**
20	666	87	**425**
30	589	72	**450**
45	520	51	**500**
60	476	38	**550**
75	445	28	**600**
90	421	22	**650**
120	386	17	**700**
150	360	14	**750**
180	341	11	**800**
240	312	7	**900**
300	291	5	**1,000**

Tool Life Equation

$$\text{Tool Life (Minutes)} = 3.52E{+}10 \times \text{Speed (fpm)}^{-3.274}$$

Tool Life Analysis

Dataset: FloJet Coolant on 4340 Steel with Carbide Tooling

Test Parameters

Work Material:	4340 Steel, 320-340, BHN		
Operation:	Turning	**Cut Type:**	O.D. Roughing - FLOJET
Cutting Tool:	CNMA-432, Grade 415	**Cutting Fluid:**	Trim_Sol (20:1);FloJet Application
Part Diameter:	6.00 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.005 ipr		
Life Units:	Minutes (Original)		
Life Criterion:	0.015" Uniform or 0.030" Local Wear		

Tool Life Data

Feed (ipt)	Speed (fpm) 450	500	600	750	900	1,200	
0.005	**104.0**		**42.0**	**33.0**	**14.0**	**6.5**	Tool Life (Minutes)
0.005					**15.0**	**6.3**	

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.005	Estimated Life (Minutes) for Feed of 0.005	Desired Speed
10	1,037	150	**400**
20	812	126	**425**
30	704	107	**450**
45	611	79	**500**
60	552	61	**550**
75	510	47	**600**
90	478	38	**650**
120	432	31	**700**
150	400	25	**750**
180	375	21	**800**
240	339	15	**900**
300	313	11	**1,000**

Tool Life Equation

$$\text{Tool Life (Minutes)} = 3.67E{+}09 \times \text{Speed (fpm)}^{-2.840}$$

Tool Life Analysis

Dataset: FloJet w/o CO2 on 4340 Steel with Carbide Tooling

Test Parameters

Work Material: 4340 Steel, 320-340, BHN
Operation: Turning — **Cut Type:** O.D. Roughing - FLOOD
Cutting Tool: CNMA-432, Grade 415 — **Cutting Fluid:** Trim_Sol (20:1); FloJet w/o CO2
Part Diameter: 6.00 Inch — **Depth of Cut:** 0.100 Inch
Feed Rate: 0.005 ipr
Life Units: Minutes **(Original)**
Life Criterion: 0.015" Uniform or 0.030" Local Wear

Tool Life Data

Feed (ipt)	Speed (fpm) 500	750	900	
0.005	36.0	10.0	4.0	Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.005	Estimated Life (Minutes) for Feed of 0.005	Desired Speed
10	720	85	400
20	595	68	425
30	532	55	450
45	476	38	500
60	440	27	550
75	414	19	600
90	394	15	650
120	364	11	700
150	342	9	750
180	326	7	800
240	301	4	900
300	283	3	1,000

Tool Life Equation

$$\text{Tool Life (Minutes)} = 2.54E{+}11 \times \text{Speed (fpm)}^{-3.642}$$

MINIMUM COST MACHINING DATA

Dataset: FloJet Coolant on 4340 Steel with Carbide Tooling

	Feed:			Feed: 0.005 ipt			Feed:		
Econ Ratio	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min
1.0	Zero	Max.	Max.	1.8	1,882	11.3	Zero	Max.	Max.
1.5	Zero	Max.	Max.	2.8	1,632	9.8	Zero	Max.	Max.
2.0	Zero	Max.	Max.	3.7	1,475	8.8	Zero	Max.	Max.
2.5	Zero	Max.	Max.	4.6	1,363	8.2	Zero	Max.	Max.
3.0	Zero	Max.	Max.	5.5	1,278	7.7	Zero	Max.	Max.
3.5	Zero	Max.	Max.	6.4	1,211	7.3	Zero	Max.	Max.
4.0	Zero	Max.	Max.	7.4	1,155	6.9	Zero	Max.	Max.
4.5	Zero	Max.	Max.	8.3	1,108	6.6	Zero	Max.	Max.
5.0	Zero	Max.	Max.	9.2	1,068	6.4	Zero	Max.	Max.
5.5	Zero	Max.	Max.	10.1	1,033	6.2	Zero	Max.	Max.
6.0	Zero	Max.	Max.	11.0	1,001	6.0	Zero	Max.	Max.
6.5	Zero	Max.	Max.	12.0	974	5.8	Zero	Max.	Max.
7.0	Zero	Max.	Max.	12.9	949	5.7	Zero	Max.	Max.
7.5	Zero	Max.	Max.	13.8	926	5.6	Zero	Max.	Max.
8.0	Zero	Max.	Max.	14.7	905	5.4	Zero	Max.	Max.
8.5	Zero	Max.	Max.	15.6	886	5.3	Zero	Max.	Max.
9.0	Zero	Max.	Max.	16.6	868	5.2	Zero	Max.	Max.
9.5	Zero	Max.	Max.	17.5	852	5.1	Zero	Max.	Max.
10.0	Zero	Max.	Max.	18.4	837	5.0	Zero	Max.	Max.
11.0	Zero	Max.	Max.	20.2	809	4.9	Zero	Max.	Max.
12.0	Zero	Max.	Max.	22.1	785	4.7	Zero	Max.	Max.
13.0	Zero	Max.	Max.	23.9	763	4.6	Zero	Max.	Max.
14.0	Zero	Max.	Max.	25.8	743	4.5	Zero	Max.	Max.
15.0	Zero	Max.	Max.	27.6	725	4.4	Zero	Max.	Max.
16.0	Zero	Max.	Max.	29.4	709	4.3	Zero	Max.	Max.
17.0	Zero	Max.	Max.	31.3	694	4.2	Zero	Max.	Max.
18.0	Zero	Max.	Max.	33.1	680	4.1	Zero	Max.	Max.
19.0	Zero	Max.	Max.	35.0	667	4.0	Zero	Max.	Max.
20.0	Zero	Max.	Max.	36.8	655	3.9	Zero	Max.	Max.
21.0	Zero	Max.	Max.	38.6	644	3.9	Zero	Max.	Max.
22.0	Zero	Max.	Max.	40.5	634	3.8	Zero	Max.	Max.
23.0	Zero	Max.	Max.	42.3	624	3.7	Zero	Max.	Max.
24.0	Zero	Max.	Max.	44.2	615	3.7	Zero	Max.	Max.

NOTE: These RATE and LIFE values are per tooth. Multiply by number of teeth to get actual LIFE and RATE!

MINIMUM COST MACHINING DATA

Dataset: Flood Coolant on 4340 Steel with Carbide Tooling

	Feed:			Feed: 0.005 ipt			Feed:		
Econ Ratio	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min
1.0	Zero	Max.	Max.	2.3	1,295	7.8	Zero	Max.	Max.
1.5	Zero	Max.	Max.	3.4	1,144	6.9	Zero	Max.	Max.
2.0	Zero	Max.	Max.	4.5	1,048	6.3	Zero	Max.	Max.
2.5	Zero	Max.	Max.	5.7	979	5.9	Zero	Max.	Max.
3.0	Zero	Max.	Max.	6.8	926	5.6	Zero	Max.	Max.
3.5	Zero	Max.	Max.	8.0	883	5.3	Zero	Max.	Max.
4.0	Zero	Max.	Max.	9.1	848	5.1	Zero	Max.	Max.
4.5	Zero	Max.	Max.	10.2	818	4.9	Zero	Max.	Max.
5.0	Zero	Max.	Max.	11.4	792	4.8	Zero	Max.	Max.
5.5	Zero	Max.	Max.	12.5	769	4.6	Zero	Max.	Max.
6.0	Zero	Max.	Max.	13.6	749	4.5	Zero	Max.	Max.
6.5	Zero	Max.	Max.	14.8	731	4.4	Zero	Max.	Max.
7.0	Zero	Max.	Max.	15.9	715	4.3	Zero	Max.	Max.
7.5	Zero	Max.	Max.	17.1	700	4.2	Zero	Max.	Max.
8.0	Zero	Max.	Max.	18.2	686	4.1	Zero	Max.	Max.
8.5	Zero	Max.	Max.	19.3	673	4.0	Zero	Max.	Max.
9.0	Zero	Max.	Max.	20.5	662	4.0	Zero	Max.	Max.
9.5	Zero	Max.	Max.	21.6	651	3.9	Zero	Max.	Max.
10.0	Zero	Max.	Max.	22.7	641	3.8	Zero	Max.	Max.
11.0	Zero	Max.	Max.	25.0	622	3.7	Zero	Max.	Max.
12.0	Zero	Max.	Max.	27.3	606	3.6	Zero	Max.	Max.
13.0	Zero	Max.	Max.	29.6	591	3.5	Zero	Max.	Max.
14.0	Zero	Max.	Max.	31.8	578	3.5	Zero	Max.	Max.
15.0	Zero	Max.	Max.	34.1	566	3.4	Zero	Max.	Max.
16.0	Zero	Max.	Max.	36.4	555	3.3	Zero	Max.	Max.
17.0	Zero	Max.	Max.	38.7	545	3.3	Zero	Max.	Max.
18.0	Zero	Max.	Max.	40.9	535	3.2	Zero	Max.	Max.
19.0	Zero	Max.	Max.	43.2	527	3.2	Zero	Max.	Max.
20.0	Zero	Max.	Max.	45.5	519	3.1	Zero	Max.	Max.
21.0	Zero	Max.	Max.	47.8	511	3.1	Zero	Max.	Max.
22.0	Zero	Max.	Max.	50.0	504	3.0	Zero	Max.	Max.
23.0	Zero	Max.	Max.	52.3	497	3.0	Zero	Max.	Max.
24.0	Zero	Max.	Max.	54.6	490	2.9	Zero	Max.	Max.

NOTE: These RATE and LIFE values are per tooth. Multiply by number of teeth to get actual LIFE and RATE!

Tool Life Analysis

Dataset: Flood Coolant on 17-4 PH with Carbide Tooling

Test Parameters

Work Material:	17-4 PH		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432 Grade 415	**Cutting Fluid:**	Trim_Sol (20:1); Flood Application
Part Diameter:	4.00 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.008 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	0.015" Uniform or 0.025" Local Wear		

Tool Life Data

Feed (ipr)	**Speed (fpm)** 300	400	450	500	600	
0.008	**99.0**	**84.0**	**46.0**	**18.5**	**11.5**	**Tool Life (Minutes)**
0.008				**26.5**	**12.5**	

Predicted Tool Life

Desired Life	**Estimated Speed (fpm) for Feed of 0.008**	**Estimated Life (Minutes) for Feed of 0.008**	**Desired Speed**
5	800	138	**300**
10	652	106	**325**
15	579	82	**350**
20	531	65	**375**
30	471	52	**400**
40	433	43	**425**
50	405	35	**450**
60	384	29	**475**
75	360	25	**500**
90	341	18	**550**
120	313	13	**600**
180	278	8	**700**

Tool Life Equation

$$\text{Tool Life (Minutes)} = 3.33E+10 \times \text{Speed (fpm)}^{-3.383}$$

Tool Life Analysis

Dataset: FloJet Coolant on 17-4 PH with Carbide Tooling

Test Parameters

Work Material: 17-4 PH

Operation: Turning **Cut Type:** Semi-Finish

Cutting Tool: CNMA-432 Grade 415 **Cutting Fluid:** Trim_Sol (20:1); FloJet Application

Part Diameter: 4.00 Inch **Depth of Cut:** 0.100 Inch

Feed Rate: 0.008 ipr

Life Units: Minutes **(Original)**

Life Criterion: 0.015" Uniform or 0.025" Local Wear

Tool Life Data

Tool Life (Minutes)

Feed (ipr)	Speed (fpm) 450	475	500	600	700
0.008	**112.0**	**58.0**	**55.0**	**21.0**	**11.5**
0.008			**44.0**	**20.0**	**9.0**

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.008	Estimated Life (Minutes) for Feed of 0.008	Desired Speed
5	801	664	**300**
10	697	446	**325**
15	642	308	**350**
20	606	219	**375**
30	559	158	**400**
40	527	117	**425**
50	504	88	**450**
60	486	67	**475**
75	465	52	**500**
90	448	32	**550**
120	423	21	**600**
180	390	10	**700**

Tool Life Equation

$$\text{Tool Life (Minutes)} = 1.43E{+}15 \times \text{Speed (fpm)}^{-4.979}$$

Tool Life Analysis

Dataset: FloJet wo/CO2 on 17-4 PH with Carbide Tooling

Test Parameters

Work Material:	17-4 PH		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432 Grade 415	**Cutting Fluid:**	Trim_Sol (20:1); FloJet w/o CO2
Part Diameter:	4.00 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.008 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	0.015" Uniform or 0.025" Local Wear		

Tool Life Data

Feed (ipr)	Speed (fpm) 450	500	600	700	
0.008	**110.0**	**43.0**	**18.5**	**10.0**	**Tool Life (Minutes)**

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.008	Estimated Life (Minutes) for Feed of 0.008	Desired Speed
5	783	768	300
10	686	505	325
15	635	342	350
20	601	238	375
30	556	170	400
40	527	123	425
50	505	91	450
60	488	69	475
75	467	53	500
90	451	32	550
120	427	20	600
180	396	9	700

Tool Life Equation

$$\text{Tool Life (Minutes)} = 7.71E+15 \times \text{Speed (fpm)}^{-5.249}$$

MINIMUM COST MACHINING DATA

Dataset: Flood Coolant on 17-4 PH with Carbide Tooling

	Feed:			Feed: 0.008 ipt			Feed:		
Econ Ratio	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min
1.0	Zero	Max.	Max.	2.4	996	9.6	Zero	Max.	Max.
1.5	Zero	Max.	Max.	3.6	884	8.5	Zero	Max.	Max.
2.0	Zero	Max.	Max.	4.8	812	7.8	Zero	Max.	Max.
2.5	Zero	Max.	Max.	6.0	760	7.3	Zero	Max.	Max.
3.0	Zero	Max.	Max.	7.2	720	6.9	Zero	Max.	Max.
3.5	Zero	Max.	Max.	8.3	688	6.6	Zero	Max.	Max.
4.0	Zero	Max.	Max.	9.5	661	6.4	Zero	Max.	Max.
4.5	Zero	Max.	Max.	10.7	639	6.1	Zero	Max.	Max.
5.0	Zero	Max.	Max.	11.9	619	5.9	Zero	Max.	Max.
5.5	Zero	Max.	Max.	13.1	602	5.8	Zero	Max.	Max.
6.0	Zero	Max.	Max.	14.3	587	5.6	Zero	Max.	Max.
6.5	Zero	Max.	Max.	15.5	573	5.5	Zero	Max.	Max.
7.0	Zero	Max.	Max.	16.7	561	5.4	Zero	Max.	Max.
7.5	Zero	Max.	Max.	17.9	549	5.3	Zero	Max.	Max.
8.0	Zero	Max.	Max.	19.1	539	5.2	Zero	Max.	Max.
8.5	Zero	Max.	Max.	20.3	529	5.1	Zero	Max.	Max.
9.0	Zero	Max.	Max.	21.5	520	5.0	Zero	Max.	Max.
9.5	Zero	Max.	Max.	22.6	512	4.9	Zero	Max.	Max.
10.0	Zero	Max.	Max.	23.8	505	4.8	Zero	Max.	Max.
11.0	Zero	Max.	Max.	26.2	491	4.7	Zero	Max.	Max.
12.0	Zero	Max.	Max.	28.6	478	4.6	Zero	Max.	Max.
13.0	Zero	Max.	Max.	31.0	467	4.5	Zero	Max.	Max.
14.0	Zero	Max.	Max.	33.4	457	4.4	Zero	Max.	Max.
15.0	Zero	Max.	Max.	35.8	448	4.3	Zero	Max.	Max.
16.0	Zero	Max.	Max.	38.1	439	4.2	Zero	Max.	Max.
17.0	Zero	Max.	Max.	40.5	431	4.1	Zero	Max.	Max.
18.0	Zero	Max.	Max.	42.9	424	4.1	Zero	Max.	Max.
19.0	Zero	Max.	Max.	45.3	417	4.0	Zero	Max.	Max.
20.0	Zero	Max.	Max.	47.7	411	3.9	Zero	Max.	Max.
21.0	Zero	Max.	Max.	50.1	405	3.9	Zero	Max.	Max.
22.0	Zero	Max.	Max.	52.4	400	3.8	Zero	Max.	Max.
23.0	Zero	Max.	Max.	54.8	394	3.8	Zero	Max.	Max.
24.0	Zero	Max.	Max.	57.2	390	3.7	Zero	Max.	Max.

NOTE: These RATE and LIFE values are per tooth. Multiply by number of teeth to get actual LIFE and RATE!

MINIMUM COST MACHINING DATA

Dataset: FloJet Coolant on 17-4 PH with Carbide Tooling

	Feed:			Feed: 0.008 ipt			Feed:		
Econ Ratio	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min
1.0	Zero	Max.	Max.	4.0	838	8.0	Zero	Max.	Max.
1.5	Zero	Max.	Max.	6.0	773	7.4	Zero	Max.	Max.
2.0	Zero	Max.	Max.	8.0	729	7.0	Zero	Max.	Max.
2.5	Zero	Max.	Max.	9.9	697	6.7	Zero	Max.	Max.
3.0	Zero	Max.	Max.	11.9	672	6.5	Zero	Max.	Max.
3.5	Zero	Max.	Max.	13.9	652	6.3	Zero	Max.	Max.
4.0	Zero	Max.	Max.	15.9	635	6.1	Zero	Max.	Max.
4.5	Zero	Max.	Max.	17.9	620	6.0	Zero	Max.	Max.
5.0	Zero	Max.	Max.	19.9	607	5.8	Zero	Max.	Max.
5.5	Zero	Max.	Max.	21.9	595	5.7	Zero	Max.	Max.
6.0	Zero	Max.	Max.	23.9	585	5.6	Zero	Max.	Max.
6.5	Zero	Max.	Max.	25.9	576	5.5	Zero	Max.	Max.
7.0	Zero	Max.	Max.	27.9	567	5.4	Zero	Max.	Max.
7.5	Zero	Max.	Max.	29.8	559	5.4	Zero	Max.	Max.
8.0	Zero	Max.	Max.	31.8	552	5.3	Zero	Max.	Max.
8.5	Zero	Max.	Max.	33.8	545	5.2	Zero	Max.	Max.
9.0	Zero	Max.	Max.	35.8	539	5.2	Zero	Max.	Max.
9.5	Zero	Max.	Max.	37.8	533	5.1	Zero	Max.	Max.
10.0	Zero	Max.	Max.	39.8	528	5.1	Zero	Max.	Max.
11.0	Zero	Max.	Max.	43.8	518	5.0	Zero	Max.	Max.
12.0	Zero	Max.	Max.	47.7	509	4.9	Zero	Max.	Max.
13.0	Zero	Max.	Max.	51.7	501	4.8	Zero	Max.	Max.
14.0	Zero	Max.	Max.	55.7	493	4.7	Zero	Max.	Max.
15.0	Zero	Max.	Max.	59.7	487	4.7	Zero	Max.	Max.
16.0	Zero	Max.	Max.	63.7	480	4.6	Zero	Max.	Max.
17.0	Zero	Max.	Max.	67.6	475	4.6	Zero	Max.	Max.
18.0	Zero	Max.	Max.	71.6	469	4.5	Zero	Max.	Max.
19.0	Zero	Max.	Max.	75.6	464	4.5	Zero	Max.	Max.
20.0	Zero	Max.	Max.	79.6	459	4.4	Zero	Max.	Max.
21.0	Zero	Max.	Max.	83.6	455	4.4	Zero	Max.	Max.
22.0	Zero	Max.	Max.	87.5	451	4.3	Zero	Max.	Max.
23.0	Zero	Max.	Max.	91.5	447	4.3	Zero	Max.	Max.
24.0	Zero	Max.	Max.	95.5	443	4.3	Zero	Max.	Max.

NOTE: These RATE and LIFE values are per tooth. Multiply by number of teeth to get actual LIFE and RATE!

Tool Life Analysis

Dataset: Flood Coolant onTitanium-6-4 w/Carbide Tooling

Test Parameters

Work Material:	Ti-6Al-4V		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432, Grade H13A	**Cutting Fluid:**	Trim_Sol (20:1); Flood Application
Part Diameter:	2.28 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.006 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	0.012" Uniform or 0.024" Nose Wear		

Tool Life Data

Feed (ipr)	**Speed (fpm)** 185	200	225	250	
0.006	**73.0**	**44.0**	**42.0**	**12.5**	
0.006		**43.0**		**12.0**	**Tool Life (Minutes)**

Predicted Tool Life

Desired Life	**Estimated Speed (fpm) for Feed of 0.006**	**Estimated Life (Minutes) for Feed of 0.006**	**Desired Speed**
5	301	238	**150**
10	266	101	**175**
15	247	48	**200**
20	235	25	**225**
30	218	14	**250**
40	207	8	**275**
50	199	5	**300**
60	192	3	**325**
75	185	2	**350**
90	179	1	**375**
120	170	1	**400**
180	158	1	**425**

Tool Life Equation

$$\text{Tool Life (Minutes)} = \mathbf{2.67E+14} \times \text{Speed (fpm)}^{\mathbf{-5.538}}$$

Tool Life Analysis

Dataset: FloJet on Titanium-6-4 w/Carbide Tooling

Test Parameters

Work Material:	Ti-6Al-4V		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432, Grade H13A	**Cutting Fluid:**	Trim_Sol (20:1); FloJet
Part Diameter:	2.28 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.006 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	0.012" Uniform or 0.024" Nose Wear		

Tool Life Data

Feed (ipr)	**Speed (fpm)** 200	225	250	275	300	325	
0.006	**96.0**	**54.0**	**38.0**	**24.0**	**18.0**	**15.5**	
0.006					**18.0**		**Tool Life (Minutes)**

Predicted Tool Life

Desired Life	**Estimated Speed (fpm) for Feed of 0.006**
5	422
10	353
15	317
20	295
30	265
40	246
50	232
60	222
75	209
90	200
120	185
180	167

Estimated Life (Minutes) for Feed of 0.006	**Desired Speed**
271	**150**
149	**175**
89	**200**
57	**225**
38	**250**
26	**275**
19	**300**
14	**325**
10	**350**
8	**375**
6	**400**
5	**425**

Tool Life Equation

Tool Life (Minutes) = **6.80E+10** x Speed (fpm)$^{-3.860}$

Tool Life Analysis

Dataset: FloJet wo/CO2 on Titanium-6-4 w/Carbide Tooling

Test Parameters

Work Material:	Ti-6Al-4V		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432, Grade H13A	**Cutting Fluid:**	Trim_Sol (20:1); FloJet wo/CO2
Part Diameter:	2.28 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.006 ipr		
Life Units:	Minutes (Original)		
Life Criterion:	0.012" Uniform or 0.024" Nose Wear		

Tool Life Data

Feed (ipr)	Speed (fpm) 200	250	300	325
0.006	**98.0**	**34.0**	**18.0**	**14.0**

Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.006	Estimated Life (Minutes) for Feed of 0.006	Desired Speed
5	414	292	**150**
10	348	158	**175**
15	315	92	**200**
20	293	58	**225**
30	265	38	**250**
40	246	26	**275**
50	233	18	**300**
60	223	13	**325**
75	211	10	**350**
90	201	7	**375**
120	187	6	**400**
180	169	5	**425**

Tool Life Equation

$$\text{Tool Life (Minutes)} = 1.53E+11 \times \text{Speed (fpm)}^{-4.006}$$

MINIMUM COST MACHINING DATA

Dataset: Flood Coolant onTitanium-6-4 w/Carbide Tooling

	Feed:			Feed: 0.006 ipt			Feed:		
Econ Ratio	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min
1.0	Zero	Max.	Max.	4.5	306	2.2	Zero	Max.	Max.
1.5	Zero	Max.	Max.	6.8	285	2.0	Zero	Max.	Max.
2.0	Zero	Max.	Max.	9.1	270	1.9	Zero	Max.	Max.
2.5	Zero	Max.	Max.	11.4	260	1.9	Zero	Max.	Max.
3.0	Zero	Max.	Max.	13.6	251	1.8	Zero	Max.	Max.
3.5	Zero	Max.	Max.	15.9	244	1.8	Zero	Max.	Max.
4.0	Zero	Max.	Max.	18.2	238	1.7	Zero	Max.	Max.
4.5	Zero	Max.	Max.	20.5	233	1.7	Zero	Max.	Max.
5.0	Zero	Max.	Max.	22.7	229	1.6	Zero	Max.	Max.
5.5	Zero	Max.	Max.	25.0	225	1.6	Zero	Max.	Max.
6.0	Zero	Max.	Max.	27.3	222	1.6	Zero	Max.	Max.
6.5	Zero	Max.	Max.	29.6	218	1.6	Zero	Max.	Max.
7.0	Zero	Max.	Max.	31.8	216	1.6	Zero	Max.	Max.
7.5	Zero	Max.	Max.	34.1	213	1.5	Zero	Max.	Max.
8.0	Zero	Max.	Max.	36.4	210	1.5	Zero	Max.	Max.
8.5	Zero	Max.	Max.	38.7	208	1.5	Zero	Max.	Max.
9.0	Zero	Max.	Max.	40.9	206	1.5	Zero	Max.	Max.
9.5	Zero	Max.	Max.	43.2	204	1.5	Zero	Max.	Max.
10.0	Zero	Max.	Max.	45.5	202	1.5	Zero	Max.	Max.
11.0	Zero	Max.	Max.	50.0	199	1.4	Zero	Max.	Max.
12.0	Zero	Max.	Max.	54.6	196	1.4	Zero	Max.	Max.
13.0	Zero	Max.	Max.	59.1	193	1.4	Zero	Max.	Max.
14.0	Zero	Max.	Max.	63.7	190	1.4	Zero	Max.	Max.
15.0	Zero	Max.	Max.	68.2	188	1.4	Zero	Max.	Max.
16.0	Zero	Max.	Max.	72.8	186	1.3	Zero	Max.	Max.
17.0	Zero	Max.	Max.	77.3	184	1.3	Zero	Max.	Max.
18.0	Zero	Max.	Max.	81.9	182	1.3	Zero	Max.	Max.
19.0	Zero	Max.	Max.	86.4	180	1.3	Zero	Max.	Max.
20.0	Zero	Max.	Max.	91.0	178	1.3	Zero	Max.	Max.
21.0	Zero	Max.	Max.	95.5	177	1.3	Zero	Max.	Max.
22.0	Zero	Max.	Max.	100.1	175	1.3	Zero	Max.	Max.
23.0	Zero	Max.	Max.	104.6	174	1.3	Zero	Max.	Max.
24.0	Zero	Max.	Max.	109.2	173	1.2	Zero	Max.	Max.

NOTE: These RATE and LIFE values are per tooth. Multiply by number of teeth to get actual LIFE and RATE!

MINIMUM COST MACHINING DATA

Dataset: FloJet on Titanium-6-4 w/Carbide Tooling

	Feed:			Feed: 0.006 ipt			Feed:		
Econ Ratio	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min
1.0	Zero	Max.	Max.	2.9	488	3.5	Zero	Max.	Max.
1.5	Zero	Max.	Max.	4.3	439	3.2	Zero	Max.	Max.
2.0	Zero	Max.	Max.	5.7	408	2.9	Zero	Max.	Max.
2.5	Zero	Max.	Max.	7.1	385	2.8	Zero	Max.	Max.
3.0	Zero	Max.	Max.	8.6	367	2.6	Zero	Max.	Max.
3.5	Zero	Max.	Max.	10.0	353	2.5	Zero	Max.	Max.
4.0	Zero	Max.	Max.	11.4	341	2.5	Zero	Max.	Max.
4.5	Zero	Max.	Max.	12.9	330	2.4	Zero	Max.	Max.
5.0	Zero	Max.	Max.	14.3	321	2.3	Zero	Max.	Max.
5.5	Zero	Max.	Max.	15.7	314	2.3	Zero	Max.	Max.
6.0	Zero	Max.	Max.	17.2	307	2.2	Zero	Max.	Max.
6.5	Zero	Max.	Max.	18.6	300	2.2	Zero	Max.	Max.
7.0	Zero	Max.	Max.	20.0	295	2.1	Zero	Max.	Max.
7.5	Zero	Max.	Max.	21.4	289	2.1	Zero	Max.	Max.
8.0	Zero	Max.	Max.	22.9	285	2.0	Zero	Max.	Max.
8.5	Zero	Max.	Max.	24.3	280	2.0	Zero	Max.	Max.
9.0	Zero	Max.	Max.	25.7	276	2.0	Zero	Max.	Max.
9.5	Zero	Max.	Max.	27.2	272	2.0	Zero	Max.	Max.
10.0	Zero	Max.	Max.	28.6	269	1.9	Zero	Max.	Max.
11.0	Zero	Max.	Max.	31.5	262	1.9	Zero	Max.	Max.
12.0	Zero	Max.	Max.	34.3	256	1.8	Zero	Max.	Max.
13.0	Zero	Max.	Max.	37.2	251	1.8	Zero	Max.	Max.
14.0	Zero	Max.	Max.	40.0	246	1.8	Zero	Max.	Max.
15.0	Zero	Max.	Max.	42.9	242	1.7	Zero	Max.	Max.
16.0	Zero	Max.	Max.	45.8	238	1.7	Zero	Max.	Max.
17.0	Zero	Max.	Max.	48.6	234	1.7	Zero	Max.	Max.
18.0	Zero	Max.	Max.	51.5	231	1.7	Zero	Max.	Max.
19.0	Zero	Max.	Max.	54.3	227	1.6	Zero	Max.	Max.
20.0	Zero	Max.	Max.	57.2	224	1.6	Zero	Max.	Max.
21.0	Zero	Max.	Max.	60.1	222	1.6	Zero	Max.	Max.
22.0	Zero	Max.	Max.	62.9	219	1.6	Zero	Max.	Max.
23.0	Zero	Max.	Max.	65.8	216	1.6	Zero	Max.	Max.
24.0	Zero	Max.	Max.	68.6	214	1.5	Zero	Max.	Max.

NOTE: These RATE and LIFE values are per tooth. Multiply by number of teeth to get actual LIFE and RATE!

Tool Life Analysis

Dataset: Flood Coolant on Inconel 718 w/Carbide Tooling

Test Parameters

Work Material:	Inconel 718		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432, Grade H13A	**Cutting Fluid:**	Trim_Sol (20:1); Flood Application
Part Diameter:	3.23 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	0.010" Local Wear, 0.020" Max. Wear or Tool Chip		

Tool Life Data

Feed (ipr)	**Speed (fpm)** 50	65	75	90	110	
0.004	**75.0**	**45.0**	**20.0**	**15.0**	**7.0**	**Tool Life (Minutes)**

Predicted Tool Life

Desired Life	**Estimated Speed (fpm) for Feed of 0.004**	**Estimated Life (Minutes) for Feed of 0.004**	**Desired Speed**
5	125	160	**40**
10	100	112	**45**
15	87	81	**50**
20	79	61	**55**
30	69	47	**60**
40	63	29	**70**
50	59	19	**80**
60	55	14	**90**
75	51	10	**100**
90	48	7	**110**
120	44	6	**120**
180	38	4	**130**

Tool Life Equation

$$\text{Tool Life (Minutes)} = 1.19E+07 \times \text{Speed (fpm)}^{-3.041}$$

Tool Life Analysis

Dataset: FloJet on Inconel 718 w/Carbide Tooling

Test Parameters

Work Material:	Inconel 718		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432, Grade H13A	**Cutting Fluid:**	Trim_Sol (20:1); FloJet
Part Diameter:	3.23 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes (Original)		
Life Criterion:	0.010" Local Wear, 0.020 " Max. Wear or Tool Chip		

Tool Life Data

Tool Life (Minutes)

Feed (ipr)	Speed (fpm) 65	75	90	110	125
0.004	**95.0**	**88.0**	**36.0**	**19.0**	**12.0**
0.004					**15.0**

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	169	528	40
10	136	361	45
15	120	257	50
20	110	189	55
30	97	142	60
40	89	86	70
50	83	56	80
60	78	38	90
75	73	27	100
90	69	20	110
120	63	15	120
180	56	12	130

Tool Life Equation

$$\text{Tool Life (Minutes)} = 7.98E+07 \times \text{Speed (fpm)}^{-3.233}$$

Tool Life Analysis

Dataset: FloJet wo/CO2 on Inconel 718 w/Carbide Tooling

Test Parameters

Work Material: Inconel 718
Operation: Turning — **Cut Type:** Semi-Finish
Cutting Tool: CNMA-432, Grade H13A — **Cutting Fluid:** Trim_Sol (20:1); FloJet wo/CO2
Part Diameter: 3.23 Inch — **Depth of Cut:** 0.100 Inch
Feed Rate: 0.004 ipr
Life Units: Minutes **(Original)**
Life Criterion: 0.010" Local Wear, 0.020 " Max. Wear or Tool Chip

Tool Life Data

Tool Life (Minutes)

Feed (ipr)	Speed (fpm) 80	90	110	125
0.004	67.0	40.0	19.0	8.0
0.004				16.0

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004
5	154
10	129
15	116
20	108
30	98
40	91
50	86
60	82
75	77
90	74
120	69
180	62

Estimated Life (Minutes) for Feed of 0.004	Desired Speed
1,008	40
634	45
419	50
288	55
204	60
111	70
66	80
41	90
27	100
19	110
13	120
10	130

Tool Life Equation

$$\text{Tool Life (Minutes)} = 2.07E+09 \times \text{Speed (fpm)}^{-3.940}$$

MINIMUM COST MACHINING DATA

Dataset: Flood Coolant on Inconel 718 w/Carbide Tooling

	Feed:			Feed: 0.004 ipt			Feed:		
Econ Ratio	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min
1.0	Zero	Max.	Max.	2.0	168	0.8	Zero	Max.	Max.
1.5	Zero	Max.	Max.	3.1	147	0.7	Zero	Max.	Max.
2.0	Zero	Max.	Max.	4.1	134	0.6	Zero	Max.	Max.
2.5	Zero	Max.	Max.	5.1	124	0.6	Zero	Max.	Max.
3.0	Zero	Max.	Max.	6.1	117	0.6	Zero	Max.	Max.
3.5	Zero	Max.	Max.	7.1	111	0.5	Zero	Max.	Max.
4.0	Zero	Max.	Max.	8.2	106	0.5	Zero	Max.	Max.
4.5	Zero	Max.	Max.	9.2	102	0.5	Zero	Max.	Max.
5.0	Zero	Max.	Max.	10.2	99	0.5	Zero	Max.	Max.
5.5	Zero	Max.	Max.	11.2	96	0.5	Zero	Max.	Max.
6.0	Zero	Max.	Max.	12.2	93	0.4	Zero	Max.	Max.
6.5	Zero	Max.	Max.	13.3	91	0.4	Zero	Max.	Max.
7.0	Zero	Max.	Max.	14.3	89	0.4	Zero	Max.	Max.
7.5	Zero	Max.	Max.	15.3	87	0.4	Zero	Max.	Max.
8.0	Zero	Max.	Max.	16.3	85	0.4	Zero	Max.	Max.
8.5	Zero	Max.	Max.	17.3	83	0.4	Zero	Max.	Max.
9.0	Zero	Max.	Max.	18.4	82	0.4	Zero	Max.	Max.
9.5	Zero	Max.	Max.	19.4	80	0.4	Zero	Max.	Max.
10.0	Zero	Max.	Max.	20.4	79	0.4	Zero	Max.	Max.
11.0	Zero	Max.	Max.	22.4	76	0.4	Zero	Max.	Max.
12.0	Zero	Max.	Max.	24.5	74	0.4	Zero	Max.	Max.
13.0	Zero	Max.	Max.	26.5	72	0.3	Zero	Max.	Max.
14.0	Zero	Max.	Max.	28.6	71	0.3	Zero	Max.	Max.
15.0	Zero	Max.	Max.	30.6	69	0.3	Zero	Max.	Max.
16.0	Zero	Max.	Max.	32.7	67	0.3	Zero	Max.	Max.
17.0	Zero	Max.	Max.	34.7	66	0.3	Zero	Max.	Max.
18.0	Zero	Max.	Max.	36.7	65	0.3	Zero	Max.	Max.
19.0	Zero	Max.	Max.	38.3	64	0.3	Zero	Max.	Max.
20.0	Zero	Max.	Max.	40.8	63	0.3	Zero	Max.	Max.
21.0	Zero	Max.	Max.	42.9	62	0.3	Zero	Max.	Max.
22.0	Zero	Max.	Max.	44.9	61	0.3	Zero	Max.	Max.
23.0	Zero	Max.	Max.	46.9	60	0.3	Zero	Max.	Max.
24.0	Zero	Max.	Max.	49.0	59	0.3	Zero	Max.	Max.

NOTE: These RATE and LIFE values are per tooth. Multiply by number of teeth to get actual LIFE and RATE!

MINIMUM COST MACHINING DATA

Dataset: FloJet on Inconel 718 w/Carbide Tooling

	Feed:			Feed: 0.004 ipt			Feed:		
Econ Ratio	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min	LIFE minute	Speed fpm	RATE Cu.In./min
1.0	Zero	Max.	Max.	2.2	217	1.0	Zero	Max.	Max.
1.5	Zero	Max.	Max.	3.3	191	0.9	Zero	Max.	Max.
2.0	Zero	Max.	Max.	4.5	175	0.8	Zero	Max.	Max.
2.5	Zero	Max.	Max.	5.6	163	0.8	Zero	Max.	Max.
3.0	Zero	Max.	Max.	6.7	154	0.7	Zero	Max.	Max.
3.5	Zero	Max.	Max.	7.8	147	0.7	Zero	Max.	Max.
4.0	Zero	Max.	Max.	8.9	141	0.7	Zero	Max.	Max.
4.5	Zero	Max.	Max.	10.0	136	0.7	Zero	Max.	Max.
5.0	Zero	Max.	Max.	11.2	132	0.6	Zero	Max.	Max.
5.5	Zero	Max.	Max.	12.3	128	0.6	Zero	Max.	Max.
6.0	Zero	Max.	Max.	13.4	125	0.6	Zero	Max.	Max.
6.5	Zero	Max.	Max.	14.5	122	0.6	Zero	Max.	Max.
7.0	Zero	Max.	Max.	15.6	119	0.6	Zero	Max.	Max.
7.5	Zero	Max.	Max.	16.7	116	0.6	Zero	Max.	Max.
8.0	Zero	Max.	Max.	17.9	114	0.5	Zero	Max.	Max.
8.5	Zero	Max.	Max.	19.0	112	0.5	Zero	Max.	Max.
9.0	Zero	Max.	Max.	20.1	110	0.5	Zero	Max.	Max.
9.5	Zero	Max.	Max.	21.2	108	0.5	Zero	Max.	Max.
10.0	Zero	Max.	Max.	22.3	106	0.5	Zero	Max.	Max.
11.0	Zero	Max.	Max.	24.6	103	0.5	Zero	Max.	Max.
12.0	Zero	Max.	Max.	26.8	101	0.5	Zero	Max.	Max.
13.0	Zero	Max.	Max.	29.0	98	0.5	Zero	Max.	Max.
14.0	Zero	Max.	Max.	31.3	96	0.5	Zero	Max.	Max.
15.0	Zero	Max.	Max.	33.5	94	0.5	Zero	Max.	Max.
16.0	Zero	Max.	Max.	35.7	92	0.4	Zero	Max.	Max.
17.0	Zero	Max.	Max.	38.0	90	0.4	Zero	Max.	Max.
18.0	Zero	Max.	Max.	40.2	89	0.4	Zero	Max.	Max.
19.0	Zero	Max.	Max.	42.4	87	0.4	Zero	Max.	Max.
20.0	Zero	Max.	Max.	44.7	86	0.4	Zero	Max.	Max.
21.0	Zero	Max.	Max.	46.9	85	0.4	Zero	Max.	Max.
22.0	Zero	Max.	Max.	49.1	83	0.4	Zero	Max.	Max.
23.0	Zero	Max.	Max.	51.4	82	0.4	Zero	Max.	Max.
24.0	Zero	Max.	Max.	53.6	81	0.4	Zero	Max.	Max.

NOTE: These RATE and LIFE values are per tooth. Multiply by number of teeth to get actual LIFE and RATE!

Tool Life Analysis

Dataset: Flood Coolant on Inconel 718 w/WG-300 Tooling

Test Parameters

Work Material:	Inconel 718		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNGN-434-T1, Grade WG-300	**Cutting Fluid:**	Trim_Sol (20:1); Flood Application
Part Diameter:	6.68 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	Tool Fracture or 0.125" Notch		

Tool Life Data

Feed (ipr)	Speed (fpm) 300	500	700	900	1,000	1,100	
0.004	7.2	7.0	4.0	6.0	6.0	4.0	
0.004	9.0			7.5		4.0	Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	1,006	9	200
10	173	9	250
15	62	8	300
20	30	8	350
30	11	7	400
40	5	7	450
50	3	7	500
60	2	6	600
75	1	6	700
90	1	5	800
120	0	5	900
180	0	5	1,000

Tool Life Equation

$$\text{Tool Life (Minutes)} = 76 \times \text{Speed (fpm)}^{-0.394}$$

Tool Life Analysis

Dataset: FloJet on Inconel 718 w/WG-300 Tooling

Test Parameters

Work Material:	Inconel 718		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNGN-434-T1, Grade WG-300	**Cutting Fluid:**	Trim_Sol (20:1); FloJet
Part Diameter:	6.68 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	Tool Fracture of 0.125" Notch		

Tool Life Data

Feed (ipr)	**Speed (fpm)** 300	500	700	900	1,100	
0.004	**6.0**	**3.0**	**2.8**	**1.6**	**1.0**	
0.004	**5.4**			**2.0**	**2.0**	**Tool Life (Minutes)**

Predicted Tool Life

Desired Life	**Estimated Speed (fpm) for Feed of 0.004**	**Estimated Life (Minutes) for Feed of 0.004**	**Desired Speed**
5	339	9	**200**
10	175	7	**250**
15	119	6	**300**
20	90	5	**350**
30	61	4	**400**
40	46	4	**450**
50	38	3	**500**
60	32	3	**600**
75	25	2	**700**
90	21	2	**800**
120	16	2	**900**
180	11	2	**1,000**

Tool Life Equation

$$\text{Tool Life (Minutes)} = 2{,}215 \times \text{Speed (fpm)}^{-1.046}$$

Tool Life Analysis

Dataset: FloJet wo/CO2 on Inconel 718 w/WG-300 Tooling

Test Parameters

Work Material:	Inconel 718		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNGN-434-T1, Grade WG-300	**Cutting Fluid:**	Trim_Sol (20:1); FloJet wo/CO2
Part Diameter:	6.68 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes (Original)		
Life Criterion:	Tool Failure or 0.125" Notch		

Tool Life Data

Feed (ipr)	Speed (fpm) 300	500	700	900	
0.004	5.0	3.0	2.8	2.0	Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	291	7	200
10	119	6	250
15	71	5	300
20	49	4	350
30	29	4	400
40	20	4	450
50	15	3	500
60	12	3	600
75	9	3	700
90	7	2	800
120	5	2	900
180	3	2	1,000

Tool Life Equation

$$\text{Tool Life (Minutes)} = 411 \times \text{Speed (fpm)}^{-0.777}$$

Tool Life Analysis

Dataset: Flood Coolant on Inconel 718 w/CBN Tooling

Test Parameters

Work Material:	Inconel 718		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432-L1, Grade CBN-20	**Cutting Fluid:**	Trim_Sol (20:1); Flood Application
Part Diameter:	3.23 Inch	**Depth of Cut:**	0.075 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	0.015" Local Wear		

Tool Life Data

Feed (ipr)	Speed (fpm) 500	700	900	
0.004	4.5	3.2	2.4	Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	455	8	300
10	238	7	325
15	162	7	350
20	124	6	375
30	85	6	400
40	65	5	425
50	53	5	450
60	44	5	475
75	36	5	500
90	30	4	550
120	23	4	600
180	16	3	700

Tool Life Equation

Tool Life (Minutes) = 3,417 x Speed (fpm) $^{-1.066}$

Tool Life Analysis

Dataset: FloJet on Inconel 718 w/CBN Tooling

Test Parameters

Work Material:	Inconel 718		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432-L1, Grade CBN-20	**Cutting Fluid:**	Trim_Sol (20:1); FloJet
Part Diameter:	3.60 Inch	**Depth of Cut:**	0.075 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	0.015" Local Wear		

Tool Life Data

Feed (ipr)	Speed (fpm) 500	700	900	
0.004	4.3	3.2	2.0	Tool Life (Minutes)
0.004				

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	459	9	300
10	267	8	325
15	194	7	350
20	155	6	375
30	113	6	400
40	90	6	425
50	76	5	450
60	66	5	475
75	55	4	500
90	48	4	550
120	38	4	600
180	28	3	700

Tool Life Equation

$$\text{Tool Life (Minutes)} = 12{,}676 \times \text{Speed (fpm)}^{-1.279}$$

Tool Life Analysis

Dataset: FloJet wo/CO2 on Inconel 718 w/CBN Tooling

Test Parameters

Work Material:	Inconel 718		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432-L1, Grade CBN-20	**Cutting Fluid:**	Trim_Sol (20:1); FloJet wo/CO2
Part Diameter:	3.23 Inch	**Depth of Cut:**	0.075 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	0.015" Local Wear		

Tool Life Data

Feed (ipr)	Speed (fpm) 500	700	900	
0.004	5.0	1.8	1.5	Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004		Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	478		13	300
10	344		11	325
15	284		10	350
20	247		8	375
30	204		7	400
40	178		6	425
50	160		6	450
60	147		5	475
75	132		5	500
90	121		4	550
120	105		3	600
180	87		2	700

Tool Life Equation

$$\text{Tool Life (Minutes)} = 2{,}152{,}094 \times \text{Speed (fpm)}^{-2.103}$$

Tool Life Analysis

Dataset: Flood Coolant on M-50 w/WG-300

Test Parameters

Work Material:	M-50		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNGN-434-T1 Grade WG-300	**Cutting Fluid:**	Trim_Sol (20:1); Flood Application
Part Diameter:	3.88 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes (Original)		
Life Criterion:	0.010" Local Wear, 0.020" Max. Wear or Tool Chip		

Tool Life Data

Feed (ipr)	Speed (fpm) 150	200	250	300	400	
0.004	**100.0**	**33.0**	**17.0**	**9.0**	**5.5**	Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	387	288	100
10	307	148	125
15	268	86	150
20	244	54	175
30	213	36	200
40	193	25	225
50	179	19	250
60	169	14	275
75	157	11	300
90	147	7	350
120	134	5	400
180	117	2	500

Tool Life Equation

$$\text{Tool Life (Minutes)} = 2.83E+08 \times \text{Speed (fpm)}^{-2.996}$$

Tool Life Analysis

Dataset: FloJet on M-50 w/WG-300

Test Parameters

Work Material:	M-50		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNGN-434-T1 Grade WG-300	**Cutting Fluid:**	Trim_Sol (20:1); FloJet
Part Diameter:	3.88 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes (Original)		
Life Criterion:	0.010" Local Wear, 0.020 " Max. Wear or Tool Chip		

Tool Life Data

Feed (ipr)	Speed (fpm) 200	250	300	400	
0.004	35.5	15.0	11.6	3.3	Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	361	360	100
10	293	171	125
15	260	93	150
20	238	56	175
30	211	36	200
40	193	24	225
50	181	17	250
60	171	12	275
75	160	9	300
90	152	6	350
120	139	4	400
180	123	2	500

Tool Life Equation

$$\text{Tool Life (Minutes)} = 1.64E{+}09 \times \text{Speed (fpm)}^{-3.330}$$

Tool Life Analysis

Dataset: FloJet wo/CO2 on M-50 w/WG-300

Test Parameters

Work Material:	M-50		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNGN-434-T1 Grade WG-300	**Cutting Fluid:**	Trim_Sol (20:1); FloJet wo/CO2
Part Diameter:	3.88 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes (Original)		
Life Criterion:	0.010" Local Wear, 0.020 " Max. Wear or Tool Chip		

Tool Life Data

Feed (ipr)	Speed (fpm) 200	250	400	
0.004	42.7	21.5	6.0	Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	425	293	100
10	332	156	125
15	288	94	150
20	260	61	175
30	225	42	200
40	203	30	225
50	188	22	250
60	176	17	275
75	162	13	300
90	152	9	350
120	137	6	400
180	119	3	500

Tool Life Equation

$$\text{Tool Life (Minutes)} = 1.24E+08 \times \text{Speed (fpm)}^{-2.813}$$

Tool Life Analysis

Dataset: Flood Coolant on M-50 w/CBN-20

Test Parameters

Work Material:	M-50		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432-L1, Grade CBN-20	**Cutting Fluid:**	Trim_Sol (20:1); Flood Application
Part Diameter:	3.88 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes (Original)		
Life Criterion:	0.010" Local Wear, 0.020" Max. Wear or Tool Chip		

Tool Life Data

Feed (ipr)	Speed (fpm) 200	225	250	300	400	
0.004	**30.5**	**25.0**	**20.1**	**6.0**	**1.0**	Tool Life (Minutes)

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	304	191	**150**
10	266	137	**160**
15	246	100	**170**
20	232	75	**180**
30	215	56	**190**
40	203	43	**200**
50	195	24	**225**
60	188	14	**250**
75	180	8	**275**
90	174	5	**300**
120	164	4	**325**
180	152	2	**350**

Tool Life Equation

$$\text{Tool Life (Minutes)} = 3.12\text{E}{+}13 \times \text{Speed (fpm)}^{-5.153}$$

Tool Life Analysis

Dataset: FloJet on M-50 w/CBN-20

Test Parameters

Work Material:	M-50		
Operation:	Turning	**Cut Type:**	Semi-Finish
Cutting Tool:	CNMA-432-L1, Grade CBN-20	**Cutting Fluid:**	Trim_Sol (20:1); FloJet
Part Diameter:	3.88 Inch	**Depth of Cut:**	0.100 Inch
Feed Rate:	0.004 ipr		
Life Units:	Minutes **(Original)**		
Life Criterion:	0.010" Local Wear, 0.020 " Max. Wear or Tool Chip		

Tool Life Data

Feed (ipr)	**Speed (fpm)** 200	225	250	300	
0.004	**54.0**	**20.0**	**8.0**	**12.5**	**Tool Life (Minutes)**
0.004			**11.0**		

Predicted Tool Life

Desired Life	**Estimated Speed (fpm) for Feed of 0.004**	**Estimated Life (Minutes) for Feed of 0.004**	**Desired Speed**
5	334	99	**150**
10	277	78	**160**
15	249	62	**170**
20	230	50	**180**
30	207	41	**190**
40	191	34	**200**
50	180	22	**225**
60	172	15	**250**
75	162	10	**275**
90	154	7	**300**
120	143	6	**325**
180	128	4	**350**

Tool Life Equation

$$\text{Tool Life (Minutes)} = 1.39E{+}10 \times \text{Speed (fpm)}^{-3.742}$$

Tool Life Analysis

Dataset: FloJet wo/CO2 on M-50 w/CBN-20

Test Parameters

Work Material: M-50
Operation: Turning **Cut Type:** Semi-Finish
Cutting Tool: CNMA-432-L1, Grade CBN-20 **Cutting Fluid:** Trim_Sol (20:1); FloJet wo/CO2
Part Diameter: 3.88 Inch **Depth of Cut:** 0.100 Inch
Feed Rate: 0.004 ipr
Life Units: Minutes **(Original)**
Life Criterion: 0.010" Local Wear, 0.020 " Max. Wear or Tool Chip

Tool Life Data

Feed (ipr)	Speed (fpm) 225	250	300	
0.004	**25.0**	**18.0**	**11.0**	**Tool Life (Minutes)**
0.004			**6.0**	

Predicted Tool Life

Desired Life	Estimated Speed (fpm) for Feed of 0.004	Estimated Life (Minutes) for Feed of 0.004	Desired Speed
5	340	131	150
10	286	101	160
15	258	79	170
20	240	63	180
30	217	51	190
40	202	41	200
50	191	26	225
60	182	17	250
75	172	12	275
90	165	8	300
120	153	6	325
180	139	4	350

Tool Life Equation

$$\text{Tool Life (Minutes)} = 6.50E+10 \times \text{Speed (fpm)}^{-3.996}$$

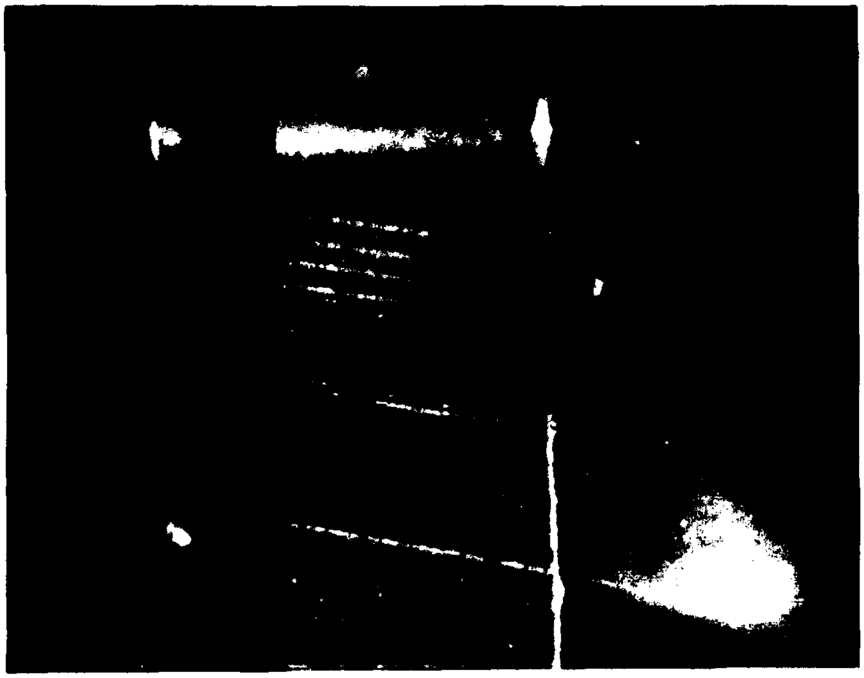
APPENDIX C

CHARACTERISTIC TOOL WEAR PATTERNS

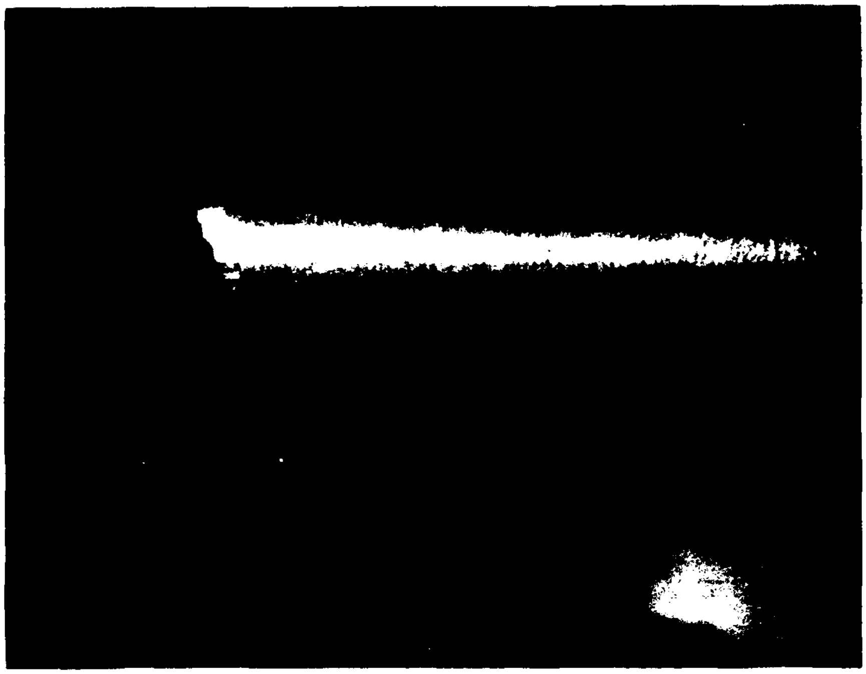
CHARACTERISTIC WEAR PATTERN
M-50 - CBN - 200 sfpm, .004 ipr

Flood Coolant -
62 minutes

***flojet* -**
90 minutes



CHARACTERISTIC WEAR PATTERN
M-50 - Ceramic - 200 sfpm, .004 ipr

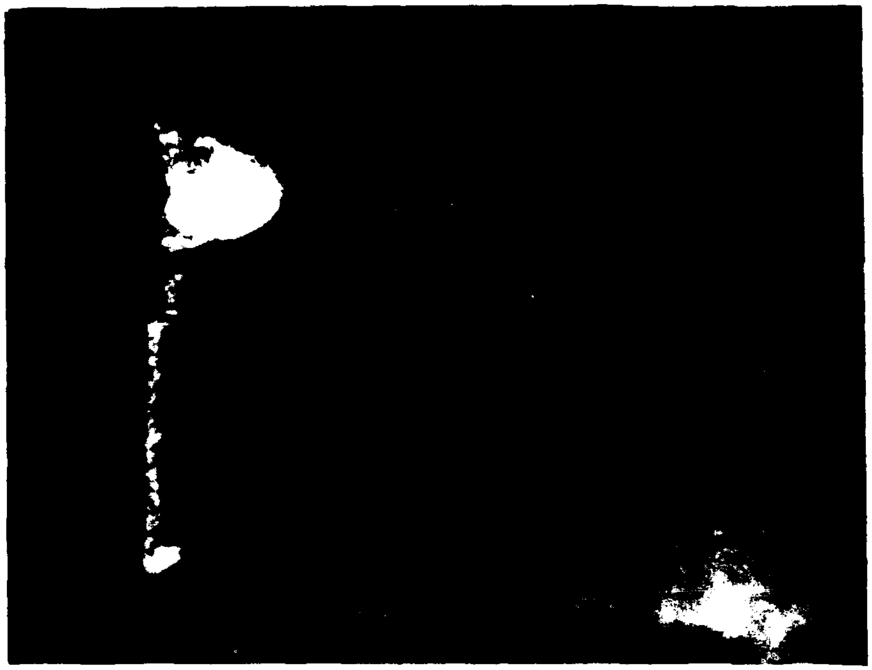


Flood Coolant - 40 minutes

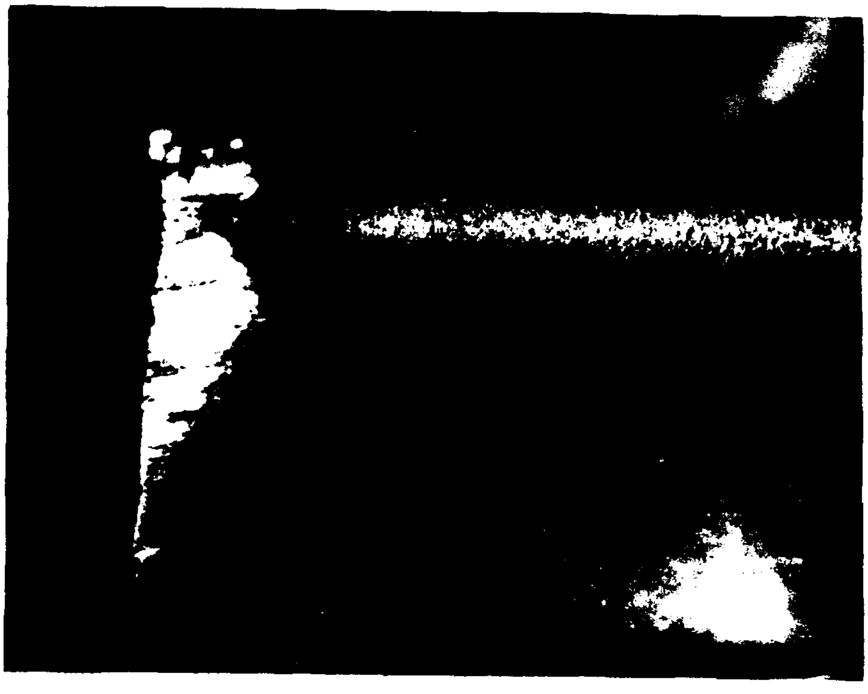
***flojet* - 35.7 minutes**

CHARACTERISTIC WEAR PATTERN
Titanium - Carbide - 200 sfpm, .006 ipr

Flood Coolant -
48 minutes



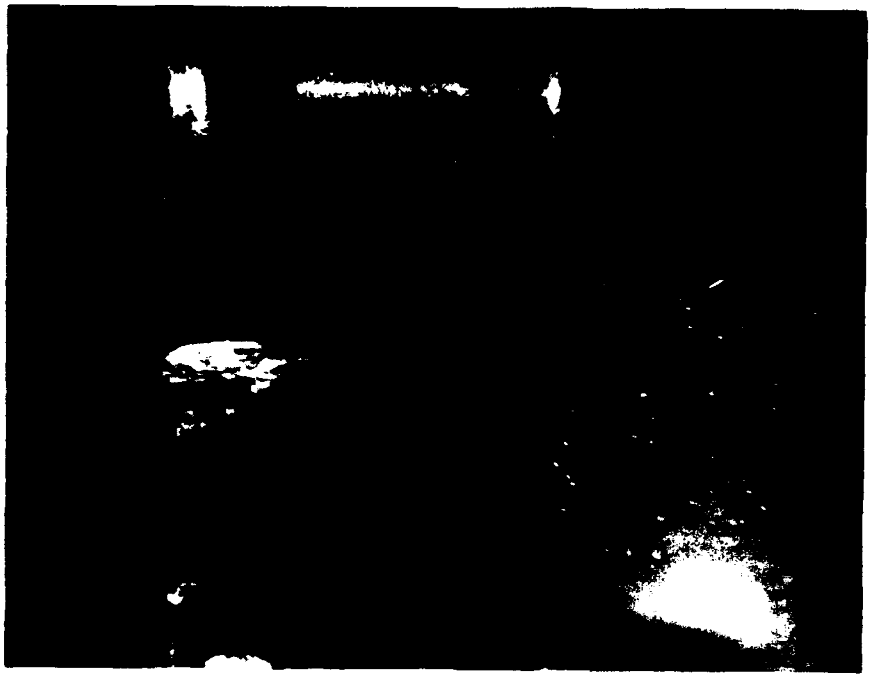
***flojet* -**
100 minutes



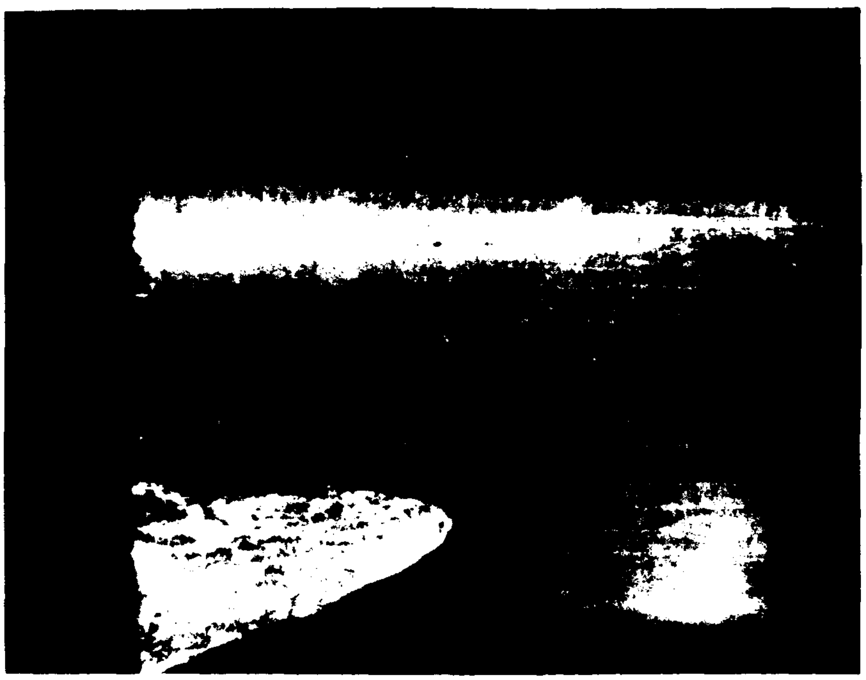
CHARACTERISTIC WEAR PATTERN
Inconel 718 - CBN - 700 sfpm, .004 ipr, .075 D.O.C.

Flood Coolant -
3 minutes

flojet **-**
3.5 minutes



CHARACTERISTIC WEAR PATTERN
Inconel 718 - Ceramic - 900 sfpm, .004 ipr



***flojet* -**
1 minute

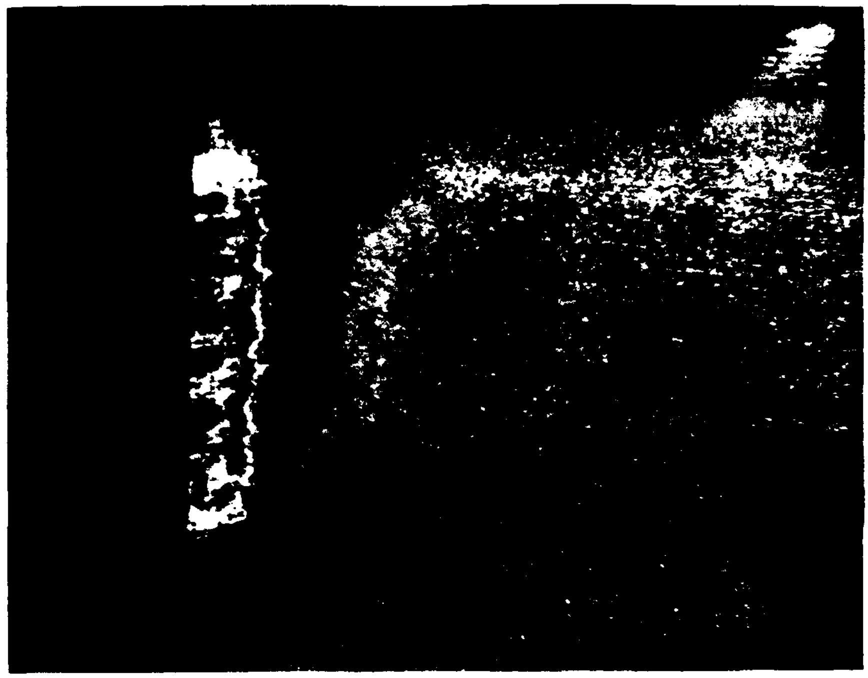
CHARACTERISTIC WEAR PATTERN
17-4 PH Stainless Steel - Carbide - 450 sfpm, .008 ipr

Flood Coolant -
50 minutes

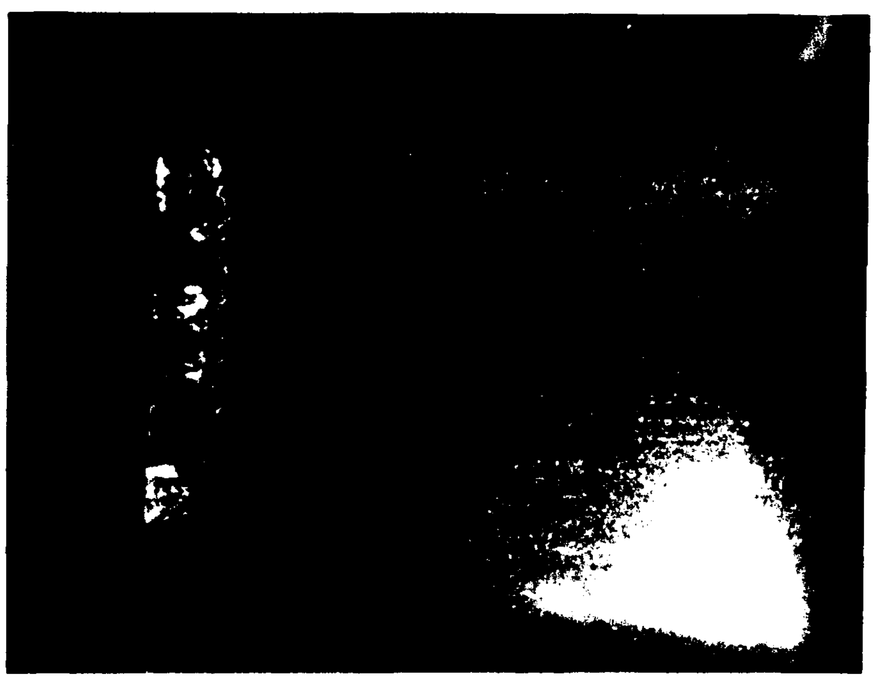
***flojet* -**
90 minutes

CHARACTERISTIC WEAR PATTERN
4340 Steel - Carbide - 600 sfpm, .005 ipr

Flood Coolant -
33 minutes

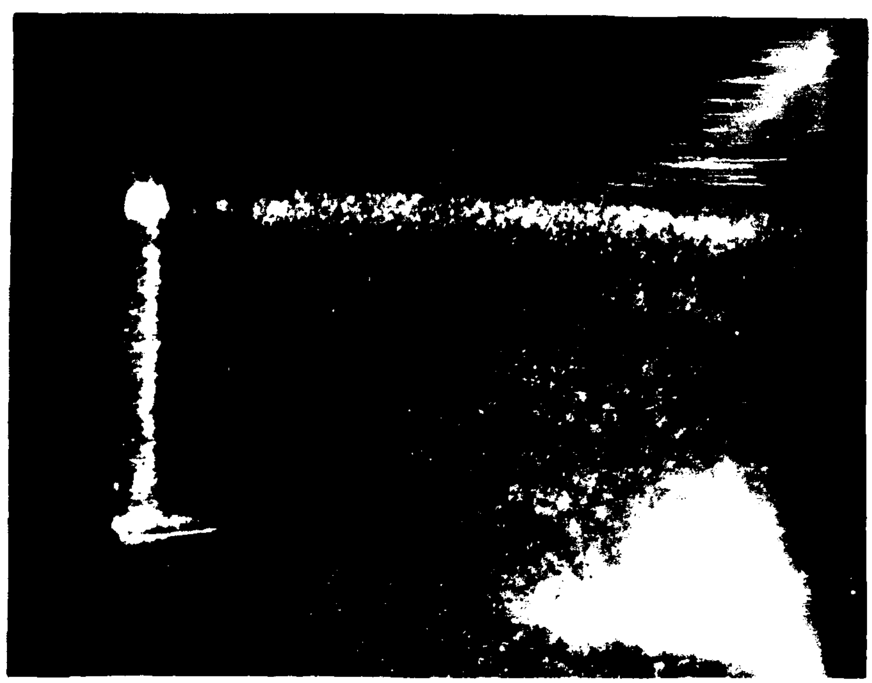


***flojet* -**
42 minutes



CHARACTERISTIC WEAR PATTERN
Inconel 718 - Carbide - 65 sfpm, .004 ipr

**Flood Coolant -
65 minutes**

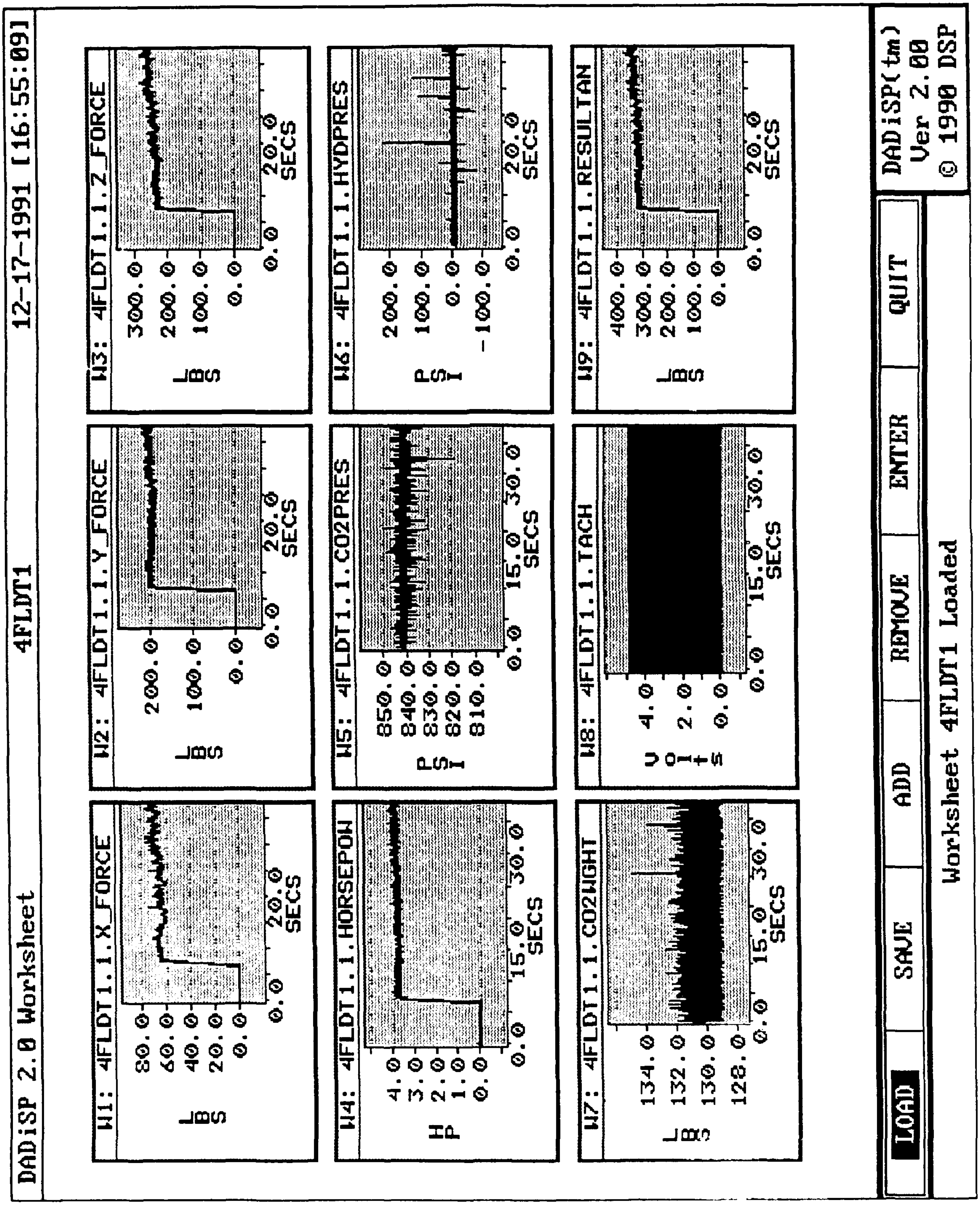


***flojet* -
100 minutes**

APPENDIX D

TEST DATA

AXIAL FORCE, HORSEPOWER, CO_2 PRESSURE, FLUID PRESSURE, CO_2 TANK WEIGHT, SPINDLE RPM, RESULTANT FORCE



DADiSP 2.0 Worksheet
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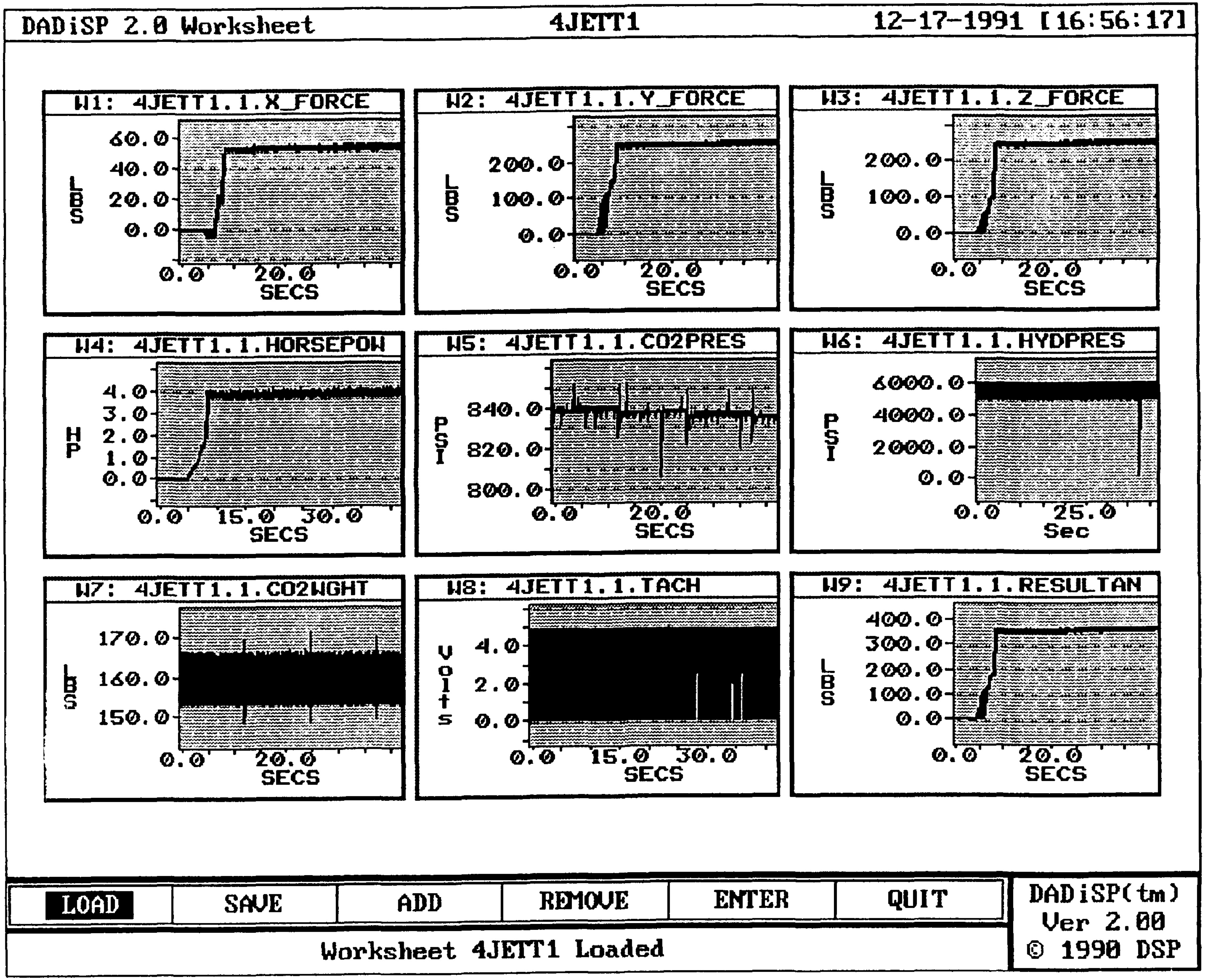
W1: 4FLDT1.1.X_FORCE
W2: 4FLDT1.1.Y_FORCE
W3: 4FLDT1.1.Z_FORCE
W4: 4FLDT1.1.HORSEPOW
W5: 4FLDT1.1.CO2PRES
W6: 4FLDT1.1.HYDPRES
W7: 4FLDT1.1.CO2WGHT
W8: 4FLDT1.1.TACH
W9: 4FLDT1.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet 4FLDT1 Loaded
DADiSP(tm)
Ver 2.00
© 1990 DSP



DADiSP 2.0 Worksheet
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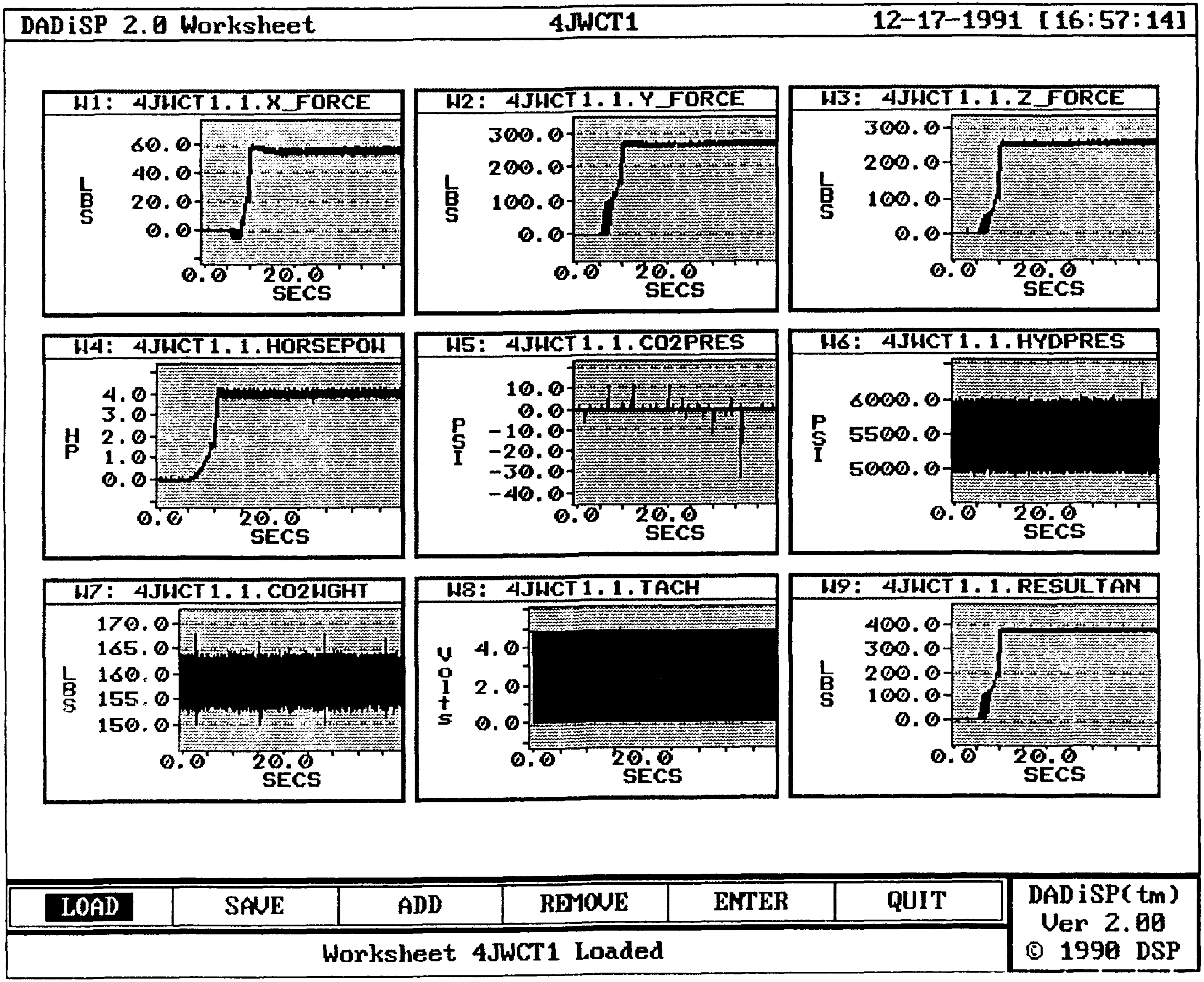
SECS
W2: 4JETT1.1.Y_FORCE
LBS
SECS
W3: 4JETT1.1.Z_FORCE
LBS
SECS
W4: 4JETT1.1.HORSEPOW
HP
SECS
W5: 4JETT1.1.CO2PRES
PSI
SECS
W6: 4JETT1.1.HYDPRES
PSI
Sec
W7: 4JETT1.1.CO2WGHT
LBS
SECS
W8: 4JETT1.1.TACH
Volts
SECS
W9: 4JETT1.1.RESULTAN
LBS
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
Ver 2.00
© 1990 DSP
Worksheet 4JETT1 Loaded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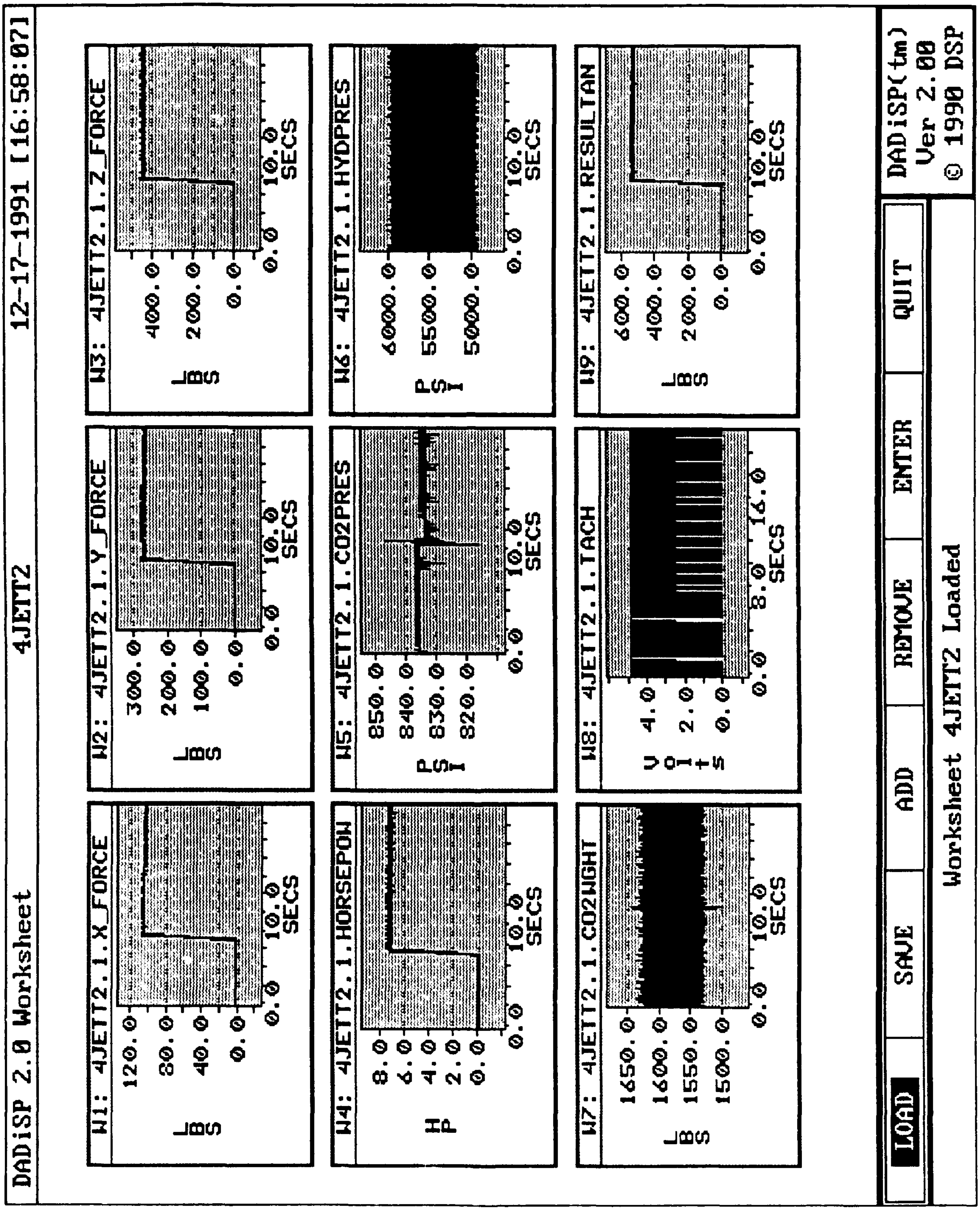
40.0
20.0
0.0
0.0
20.0
SECS
W2: 4JWCT1.1.Y_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
20.0
SECS
W3: 4JWCT1.1.Z_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
20.0
SECS
W4: 4JWCT1.1.HORSEPOW
HP
4.0
3.0
2.0
1.0
0.0
0.0
20.0
SECS
W5: 4JWCT1.1.CO2PRES
PSI
10.0
0.0
-10.0
-20.0
-30.0
-40.0
0.0
20.0
SECS
W6: 4JWCT1.1.HYDPRES
PSI
6000.0
5500.0
5000.0
0.0
20.0
SECS
W7: 4JWCT1.1.CO2WGHT
LBS
170.0
165.0
160.0
155.0
150.0
0.0
20.0
SECS
W8: 4JWCT1.1.TACH
Volts
4.0
2.0
0.0
0.0
20.0
SECS
W9: 4JWCT1.1.RESULTAN
LBS
400.0
300.0
200.0
100.0
0.0
0.0
20.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
Ver 2.00
© 1990 DSP
Worksheet 4JWCT1 Loaded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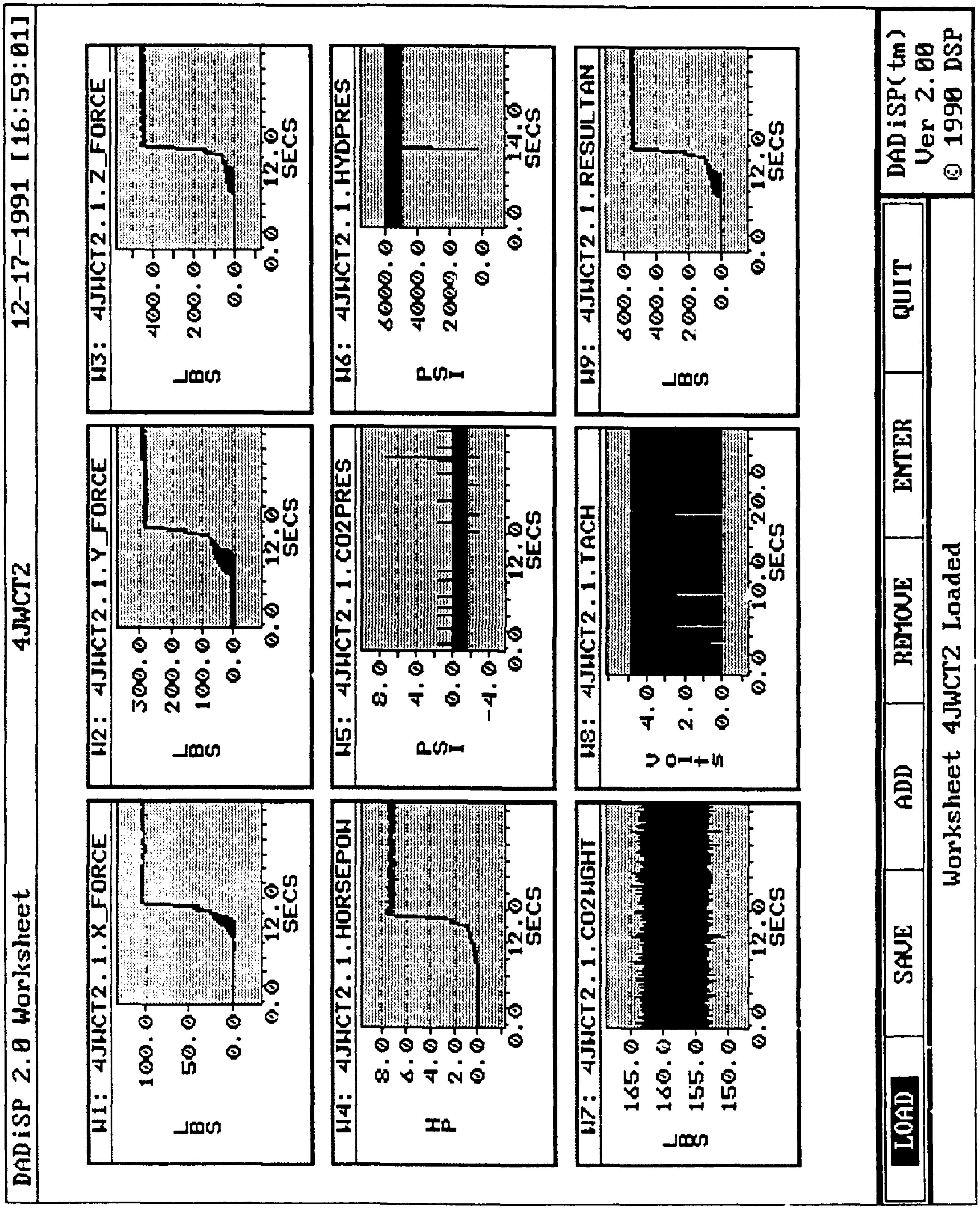
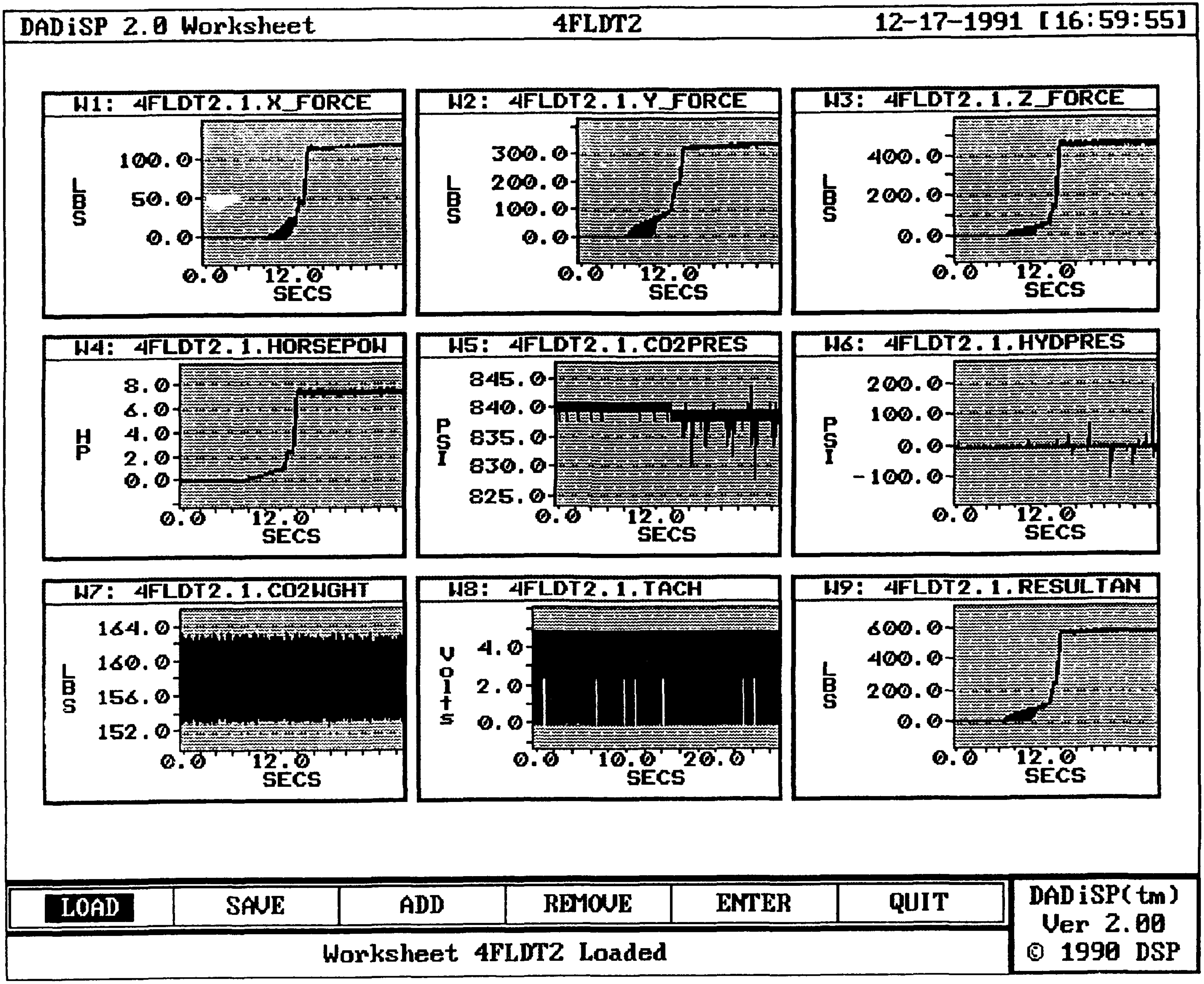
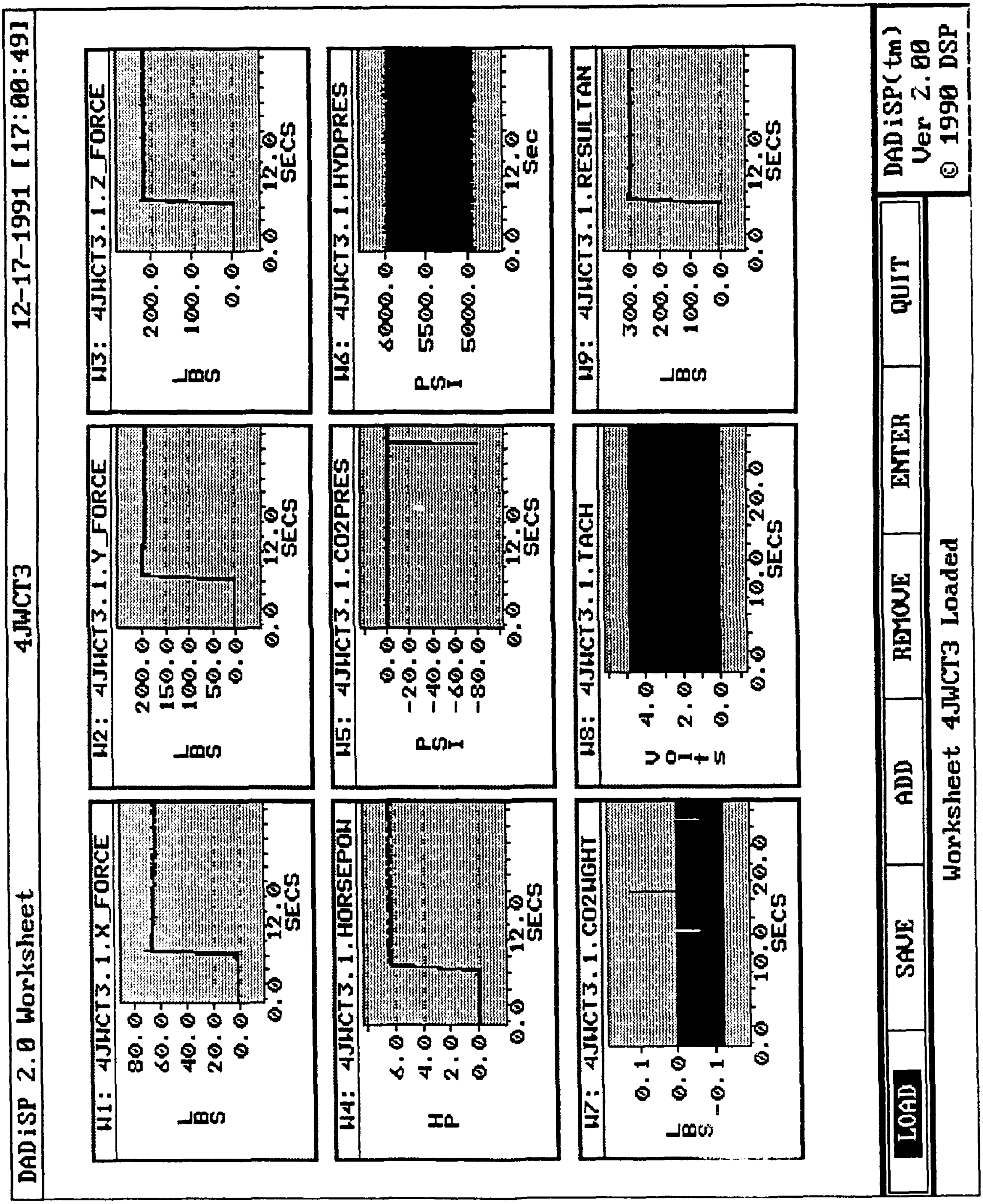
W3: 4JETT2.1.Z_FORCE
W4: 4JETT2.1.HORSEPOW
W5: 4JETT2.1.CO2PRES
W6: 4JETT2.1.HYDPRES
W7: 4JETT2.1.CO2WGHT
W8: 4JETT2.1.TACH
W9: 4JETT2.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet 4JETT2 Loaded
DADiSP(tm)
Ver 2.00
© 1990 DSP


DADiSP 2.0 Worksheet
4JWCT2
12-17-1991 [16:59:01]
W1: 4JWCT2.1.X_FORCE
W2: 4JWCT2.1.Y_FORCE
W3: 4JWCT2.1.Z_FORCE
W4: 4JWCT2.1.HORSEPOW
W5: 4JWCT2.1.CO2PRES
W6: 4JWCT2.1.HYDPRES
W7: 4JWCT2.1.CO2WGHT
W8: 4JWCT2.1.TACH
W9: 4JWCT2.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet 4JWCT2 Loaded
DADiSP(tm)
Ver 2.00
© 1990 DSP


DADiSP 2.0 Worksheet
4FLDT2
12-17-1991 [16:59:55]
W1: 4FLDT2.1.X_FORCE
LBS
100.0
50.0
0.0
0.0
12.0
SECS
W2: 4FLDT2.1.Y_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
12.0
SECS
W3: 4FLDT2.1.Z_FORCE
LBS
400.0
200.0
0.0
0.0
12.0
SECS
W4: 4FLDT2.1.HORSEPOW
HP
8.0
6.0
4.0
2.0
0.0
0.0
12.0
SECS
W5: 4FLDT2.1.CO2PRES
PSI
845.0
840.0
835.0
830.0
825.0
0.0
12.0
SECS
W6: 4FLDT2.1.HYDPRES
PSI
200.0
100.0
0.0
-100.0
0.0
12.0
SECS
W7: 4FLDT2.1.CO2WGHT
LBS
164.0
160.0
156.0
152.0
0.0
12.0
SECS
W8: 4FLDT2.1.TACH
Volts
4.0
2.0
0.0
0.0
10.0
20.0
SECS
W9: 4FLDT2.1.RESULTAN
LBS
600.0
400.0
200.0
0.0
0.0
12.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
Ver 2.00
© 1990 DSP
Worksheet 4FLDT2 Loaded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4JWCT3
12-17-1991 [17:00:49]
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LBS
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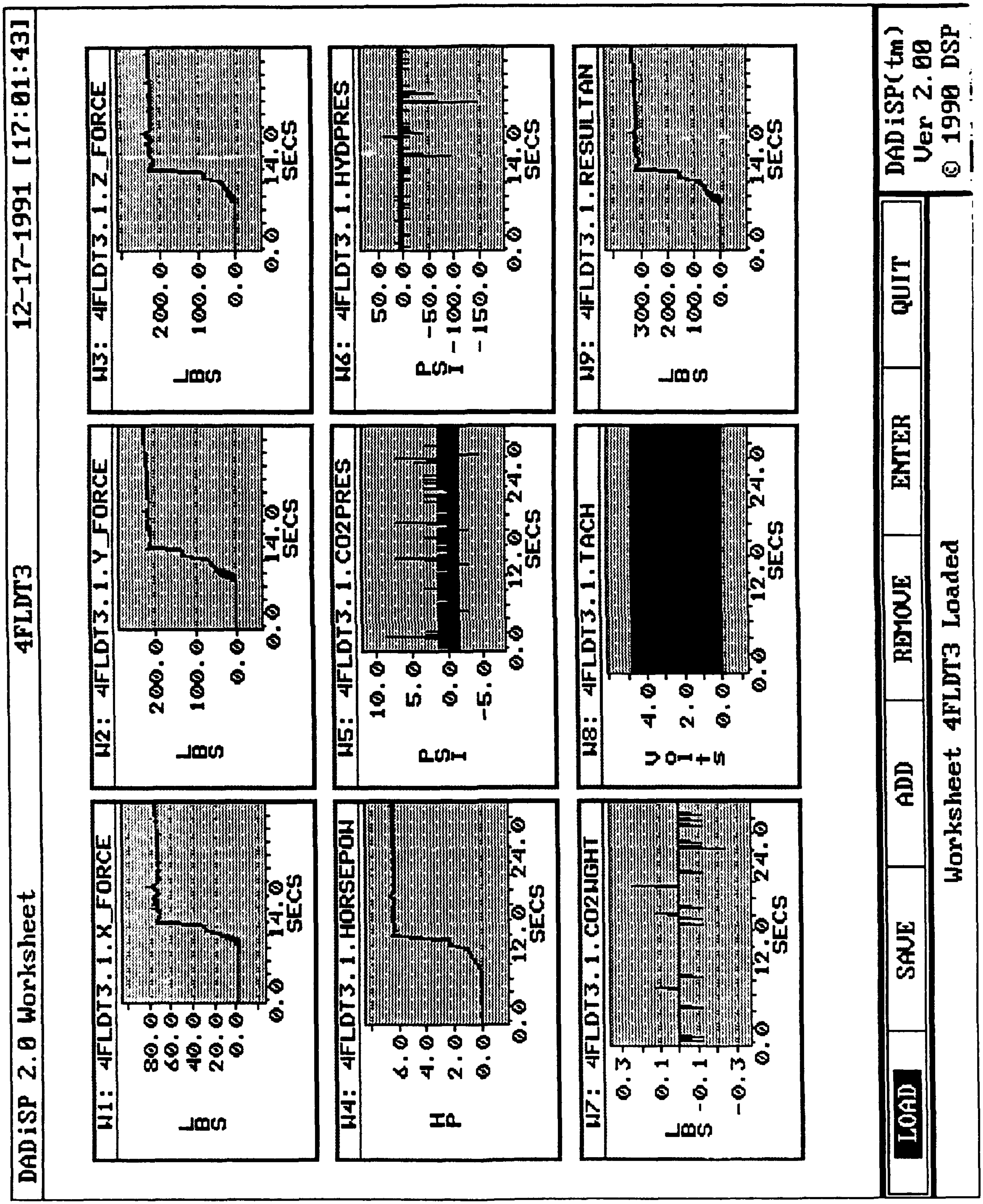
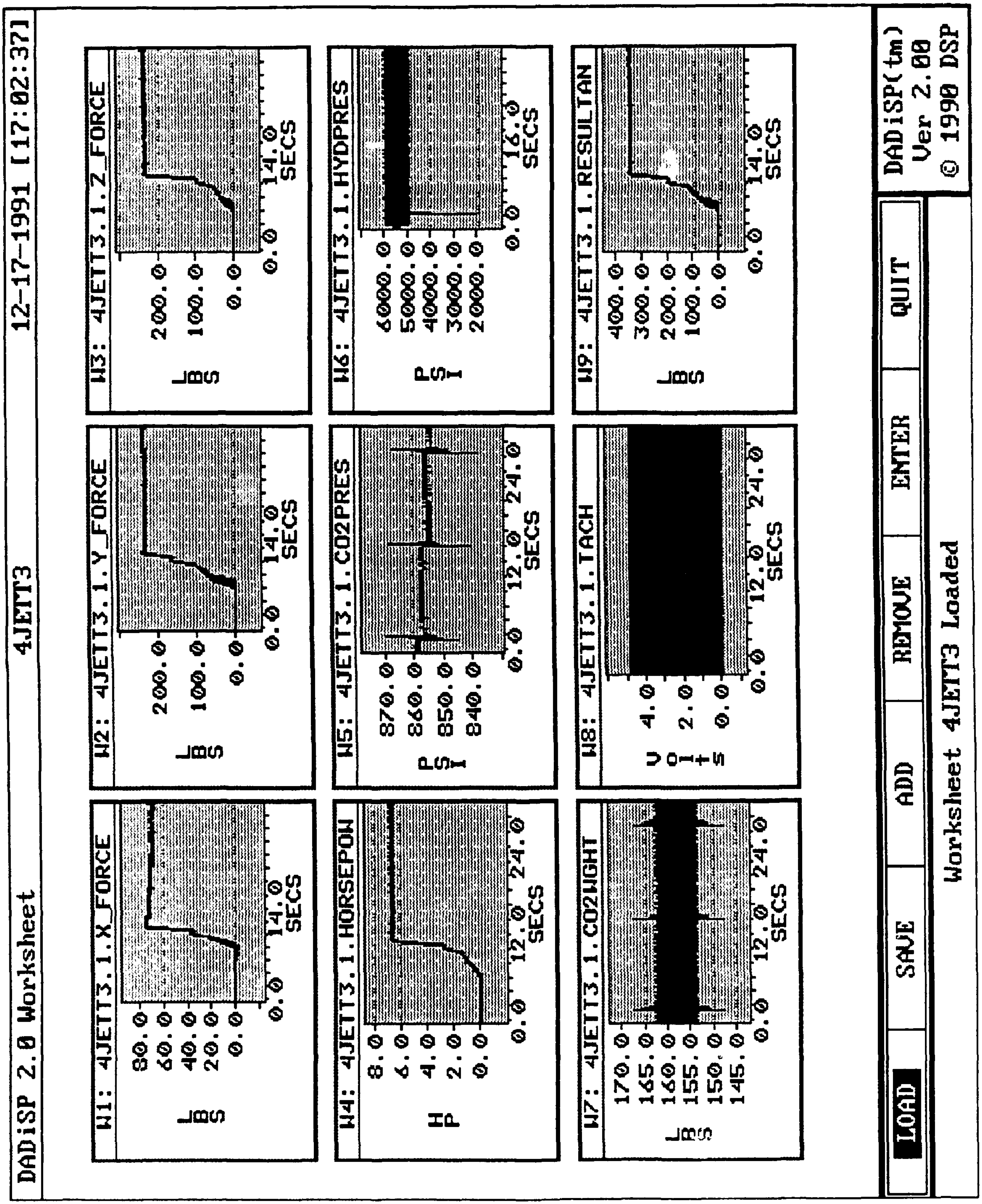
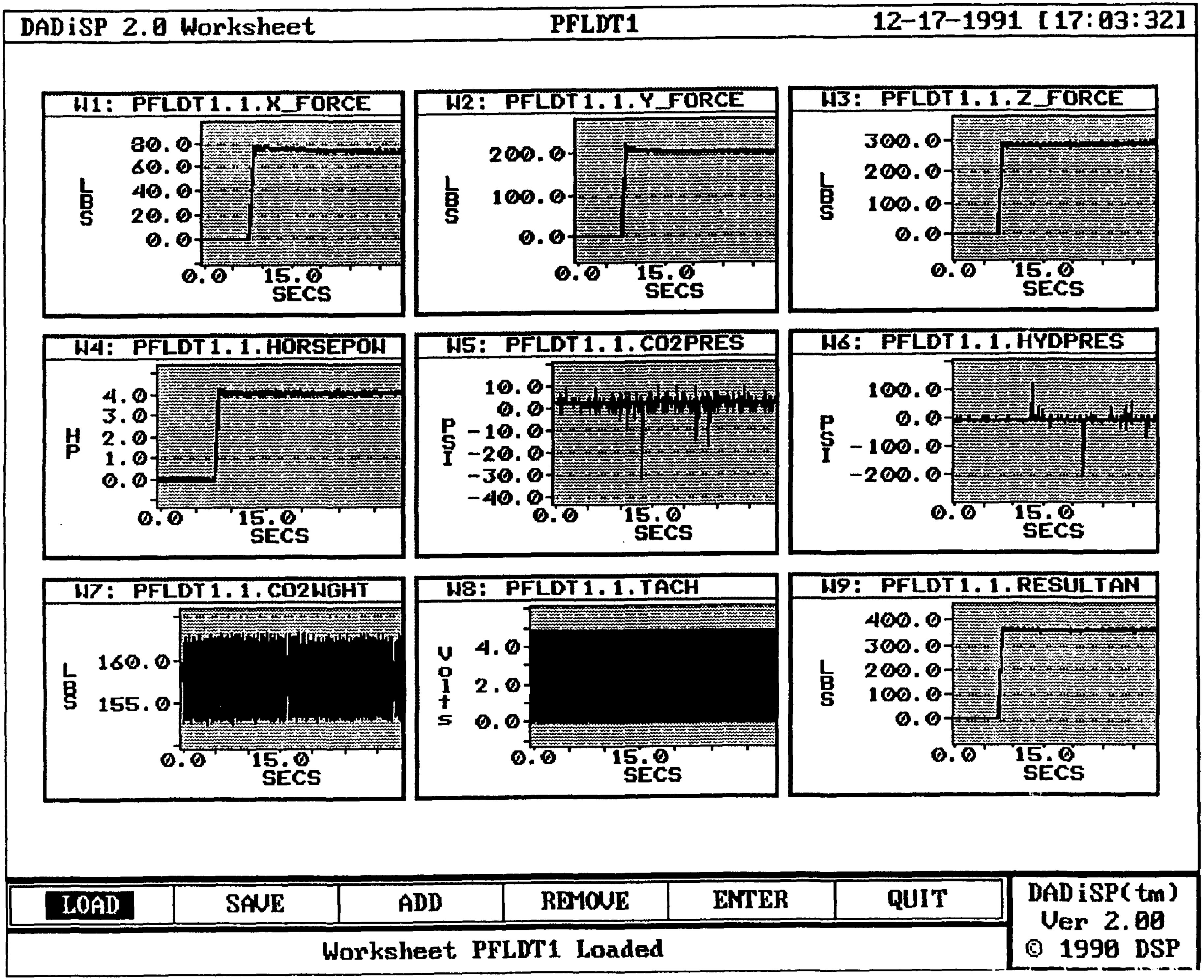
60.0
40.0
20.0
0.0
0.0
12.0
SECS
W2: 4JWCT3.1.Y_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
12.0
SECS
W3: 4JWCT3.1.Z_FORCE
LBS
200.0
100.0
0.0
0.0
12.0
SECS
W4: 4JWCT3.1.HORSEPOW
HP
6.0
4.0
2.0
0.0
0.0
12.0
SECS
W5: 4JWCT3.1.CO2PRES
PSI
0.0
-20.0
-40.0
-60.0
-80.0
0.0
12.0
SECS
W6: 4JWCT3.1.HYDPRES
PSI
6000.0
5500.0
5000.0
0.0
12.0
Sec
W7: 4JWCT3.1.CO2WGHT
LBS
0.1
0.0
-0.1
0.0
10.0
20.0
SECS
W8: 4JWCT3.1.TACH
Volts
4.0
2.0
0.0
0.0
10.0
20.0
SECS
W9: 4JWCT3.1.RESULTAN
LBS
300.0
200.0
100.0
0.0
0.0
12.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet 4JWCT3 Loaded
DADiSP(tm)
Ver 2.00
© 1990 DSP

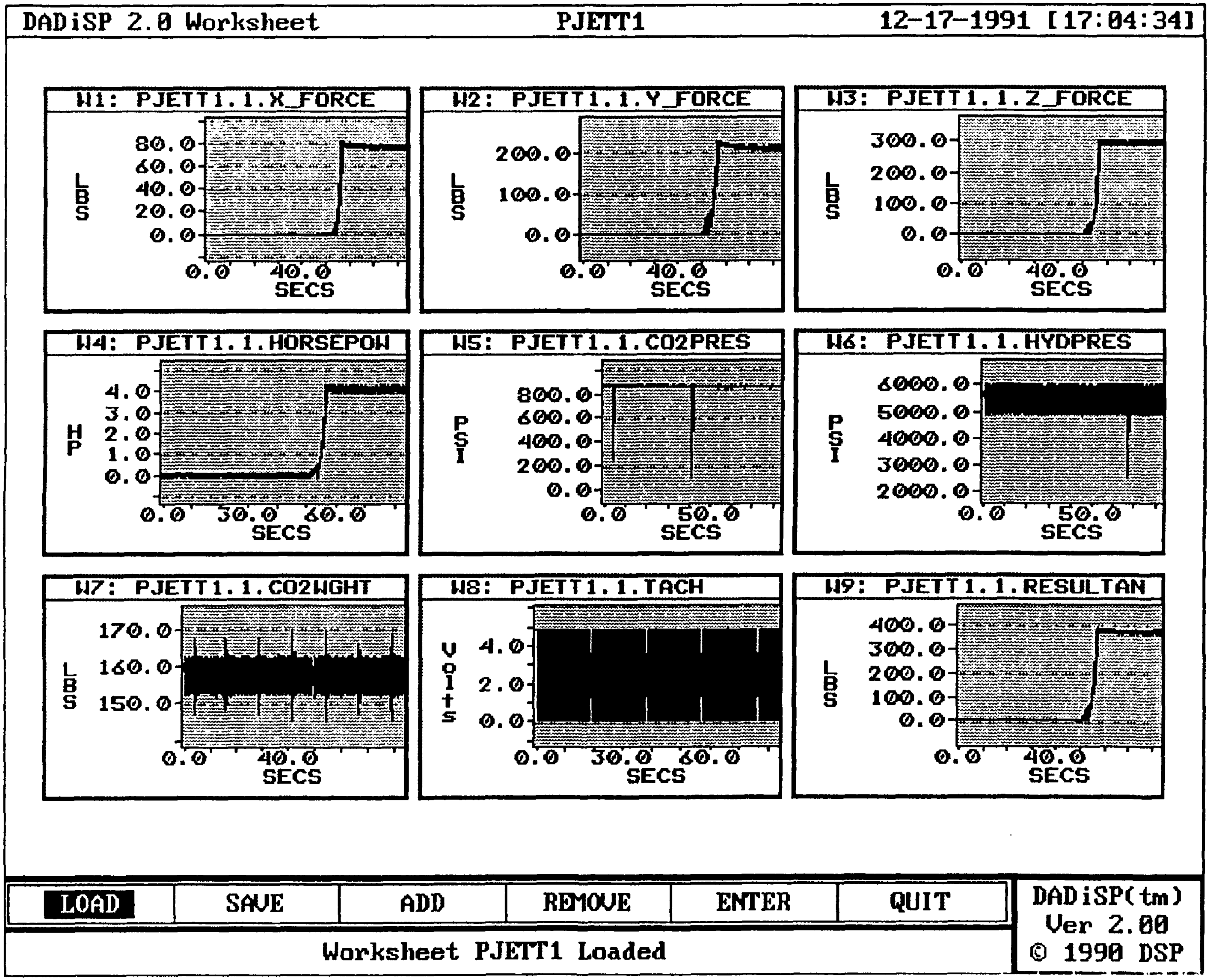


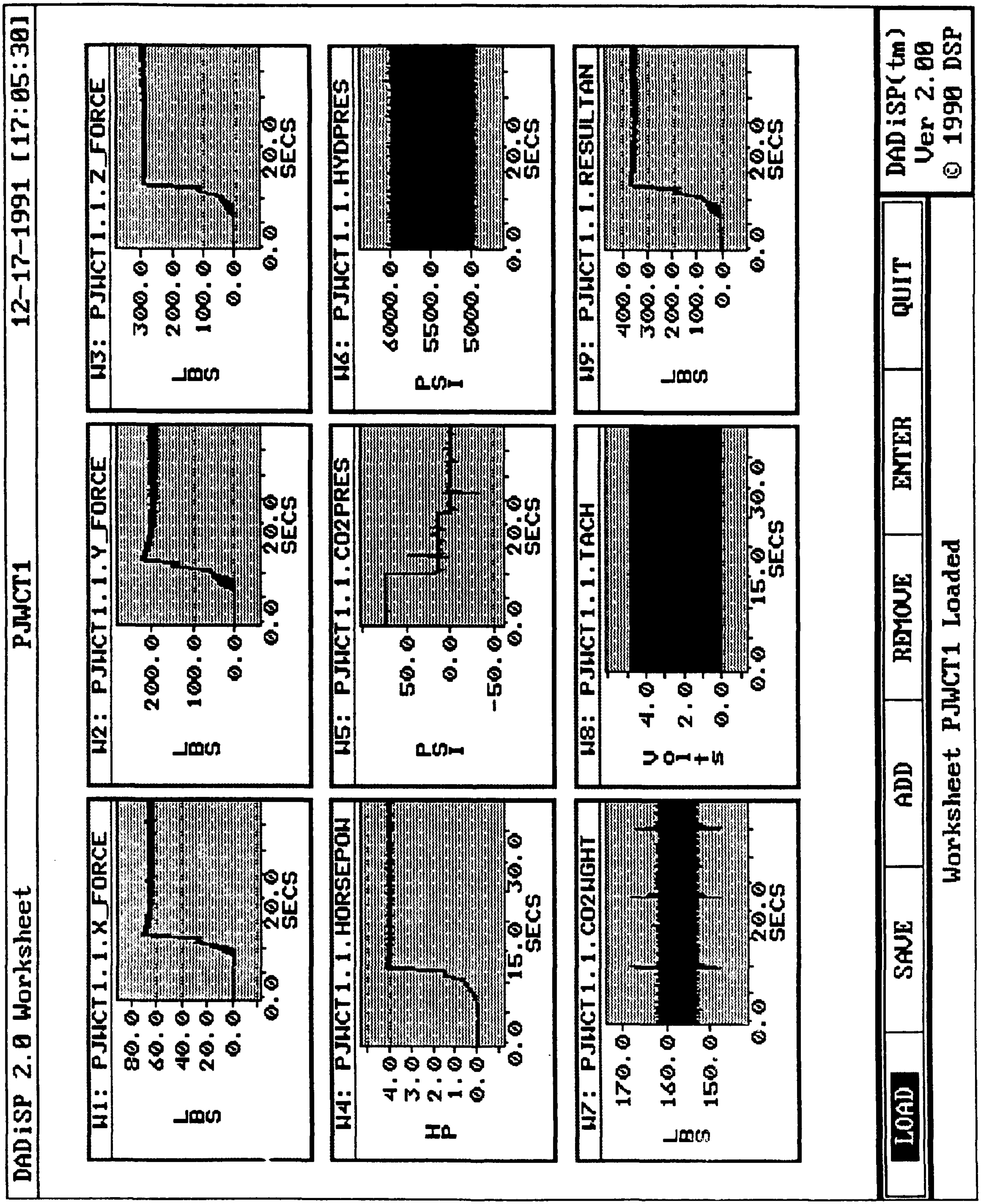
DADiSP 2.0 Worksheet
4FLDT3
12-17-1991 [17:01:43]
W1: 4FLDT3.1.X_FORCE
LBS
80.0
60.0
40.0
20.0
0.0
0.0
14.0
SECS
W2: 4FLDT3.1.Y_FORCE
LBS
200.0
100.0
0.0
0.0
14.0
SECS
W3: 4FLDT3.1.Z_FORCE
LBS
200.0
100.0
0.0
0.0
14.0
SECS
W4: 4FLDT3.1.HORSEPOW
HP
6.0
4.0
2.0
0.0
0.0
12.0
24.0
SECS
W5: 4FLDT3.1.CO2PRES
PSI
10.0
5.0
0.0
-5.0
0.0
12.0
24.0
SECS
W6: 4FLDT3.1.HYDPRES
PSI
50.0
0.0
-50.0
-100.0
-150.0
0.0
14.0
SECS
W7: 4FLDT3.1.CO2WGHT
LBS
0.3
0.1
-0.1
-0.3
0.0
12.0
24.0
SECS
W8: 4FLDT3.1.TACH
Volts
4.0
2.0
0.0
0.0
12.0
24.0
SECS
W9: 4FLDT3.1.RESULTAN
LBS
300.0
200.0
100.0
0.0
0.0
14.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet 4FLDT3 Loaded
DADiSP(tm)
Ver 2.00
© 1990 DSP


DADiSP 2.0 Worksheet
4JETT3
12-17-1991 [17:02:37]
W1: 4JETT3.1.X_FORCE
W2: 4JETT3.1.Y_FORCE
W3: 4JETT3.1.Z_FORCE
W4: 4JETT3.1.HORSEPOW
W5: 4JETT3.1.CO2PRES
W6: 4JETT3.1.HYDPRES
W7: 4JETT3.1.CO2WGHT
W8: 4JETT3.1.TACH
W9: 4JETT3.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet 4JETT3 Loaded
DADiSP(tm)
Ver 2.00
© 1990 DSP

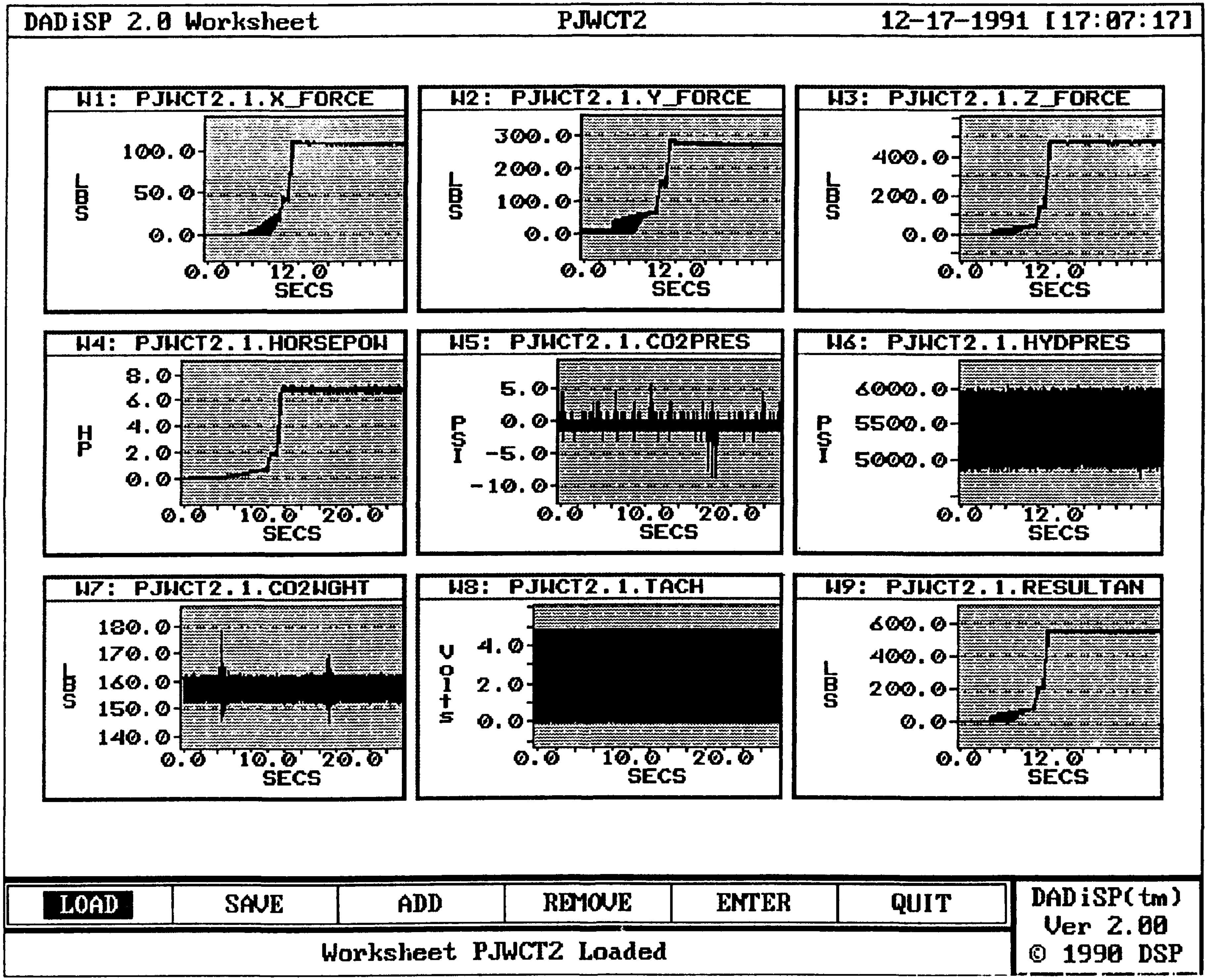


DADiSP 2.0 Worksheet
PFLDT1
12-17-1991 [17:03:32]
W1: PFLDT1.1.X_FORCE
LBS
80.0
60.0
40.0
20.0
0.0
0.0
15.0
SECS
W2: PFLDT1.1.Y_FORCE
LBS
200.0
100.0
0.0
0.0
15.0
SECS
W3: PFLDT1.1.Z_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
15.0
SECS
W4: PFLDT1.1.HORSEPOW
HP
4.0
3.0
2.0
1.0
0.0
0.0
15.0
SECS
W5: PFLDT1.1.CO2PRES
PSI
10.0
0.0
-10.0
-20.0
-30.0
-40.0
0.0
15.0
SECS
W6: PFLDT1.1.HYDPRES
PSI
100.0
0.0
-100.0
-200.0
0.0
15.0
SECS
W7: PFLDT1.1.CO2WGHT
LBS
160.0
155.0
0.0
15.0
SECS
W8: PFLDT1.1.TACH
Volts
4.0
2.0
0.0
0.0
15.0
SECS
W9: PFLDT1.1.RESULTAN
LBS
400.0
300.0
200.0
100.0
0.0
0.0
15.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
Ver 2.00
© 1990 DSP
Worksheet PFLDT1 Loaded


DADiSP 2.0 Worksheet
PJETT1
12-17-1991 [17:04:34]
W1: PJETT1.1.X_FORCE
LBS
80.0
60.0
40.0
20.0
0.0
0.0
40.0
SECS
W2: PJETT1.1.Y_FORCE
LBS
200.0
100.0
0.0
0.0
40.0
SECS
W3: PJETT1.1.Z_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
40.0
SECS
W4: PJETT1.1.HORSEPOW
HP
4.0
3.0
2.0
1.0
0.0
0.0
30.0
60.0
SECS
W5: PJETT1.1.CO2PRES
PSI
800.0
600.0
400.0
200.0
0.0
0.0
50.0
SECS
W6: PJETT1.1.HYDPRES
PSI
6000.0
5000.0
4000.0
3000.0
2000.0
0.0
50.0
SECS
W7: PJETT1.1.CO2WGHT
LBS
170.0
160.0
150.0
0.0
40.0
SECS
W8: PJETT1.1.TACH
Volts
4.0
2.0
0.0
0.0
30.0
60.0
SECS
W9: PJETT1.1.RESULTAN
LBS
400.0
300.0
200.0
100.0
0.0
0.0
40.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
Ver 2.00
© 1990 DSP
Worksheet PJETT1 Loaded



DADiSP 2.0 Worksheet
PJWCT1
12-17-1991 [17:05:30]
W1: PJWCT1.1.X_FORCE
LBS
80.0 60.0 40.0 20.0 0.0
0.0 20.0 SECS
W2: PJWCT1.1.Y_FORCE
LBS
200.0 100.0 0.0
0.0 20.0 SECS
W3: PJWCT1.1.Z_FORCE
LBS
300.0 200.0 100.0 0.0
0.0 20.0 SECS
W4: PJWCT1.1.HORSEPOW
HP
4.0 3.0 2.0 1.0 0.0
0.0 15.0 30.0 SECS
W5: PJWCT1.1.CO2PRES
PSI
50.0 0.0 -50.0
0.0 20.0 SECS
W6: PJWCT1.1.HYDPRES
PSI
6000.0 5500.0 5000.0
0.0 20.0 SECS
W7: PJWCT1.1.CO2WGHT
LBS
170.0 160.0 150.0
0.0 20.0 SECS
W8: PJWCT1.1.TACH
Volts
4.0 2.0 0.0
0.0 15.0 30.0 SECS
W9: PJWCT1.1.RESULTAN
LBS
400.0 300.0 200.0 100.0 0.0
0.0 20.0 SECS
LOAD SAVE ADD REMOVE ENTER QUIT
Worksheet PJWCT1 Loaded
DADiSP(tm) Ver 2.00 © 1990 DSP



DADiSP 2.0 Worksheet
PJWCT2
12-17-1991 [17:07:17]
W1: PJWCT2.1.X_FORCE
LBS
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50.0
0.0
0.0
12.0
SECS
W2: PJWCT2.1.Y_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
12.0
SECS
W3: PJWCT2.1.Z_FORCE
LBS
400.0
200.0
0.0
0.0
12.0
SECS
W4: PJWCT2.1.HORSEPOW
HP
8.0
6.0
4.0
2.0
0.0
0.0
10.0
20.0
SECS
W5: PJWCT2.1.CO2PRES
PSI
5.0
0.0
-5.0
-10.0
0.0
10.0
20.0
SECS
W6: PJWCT2.1.HYDPRES
PSI
6000.0
5500.0
5000.0
0.0
12.0
SECS
W7: PJWCT2.1.CO2WGHT
LBS
180.0
170.0
160.0
150.0
140.0
0.0
10.0
20.0
SECS
W8: PJWCT2.1.TACH
Volts
4.0
2.0
0.0
0.0
10.0
20.0
SECS
W9: PJWCT2.1.RESULTAN
LBS
600.0
400.0
200.0
0.0
0.0
12.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet PJWCT2 Loaded
DADiSP(tm)
Ver 2.00
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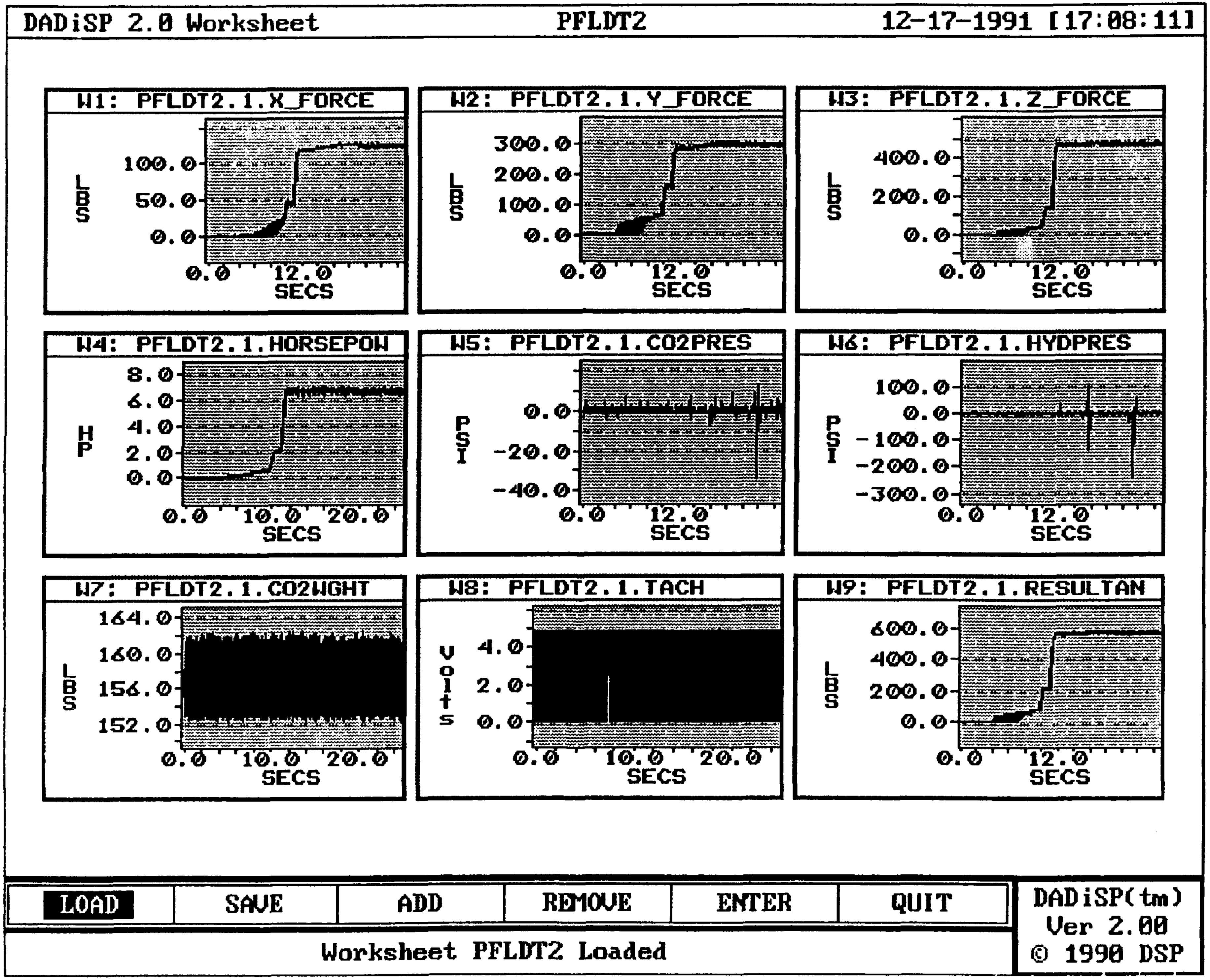
DADiSP 2.0 Worksheet
PFLDT2
12-17-1991 [17:08:11]
W1: PFLDT2.1.X_FORCE
LBS
100.0
50.0
0.0
0.0
12.0
SECS
W2: PFLDT2.1.Y_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
12.0
SECS
W3: PFLDT2.1.Z_FORCE
LBS
400.0
200.0
0.0
0.0
12.0
SECS
W4: PFLDT2.1.HORSEPOW
HP
8.0
6.0
4.0
2.0
0.0
0.0
10.0
20.0
SECS
W5: PFLDT2.1.CO2PRES
PSI
0.0
-20.0
-40.0
0.0
12.0
SECS
W6: PFLDT2.1.HYDPRES
PSI
100.0
0.0
-100.0
-200.0
-300.0
0.0
12.0
SECS
W7: PFLDT2.1.CO2WGHT
LBS
164.0
160.0
156.0
152.0
0.0
10.0
20.0
SECS
W8: PFLDT2.1.TACH
Volts
4.0
2.0
0.0
0.0
10.0
20.0
SECS
W9: PFLDT2.1.RESULTAN
LBS
600.0
400.0
200.0
0.0
0.0
12.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
Ver 2.00
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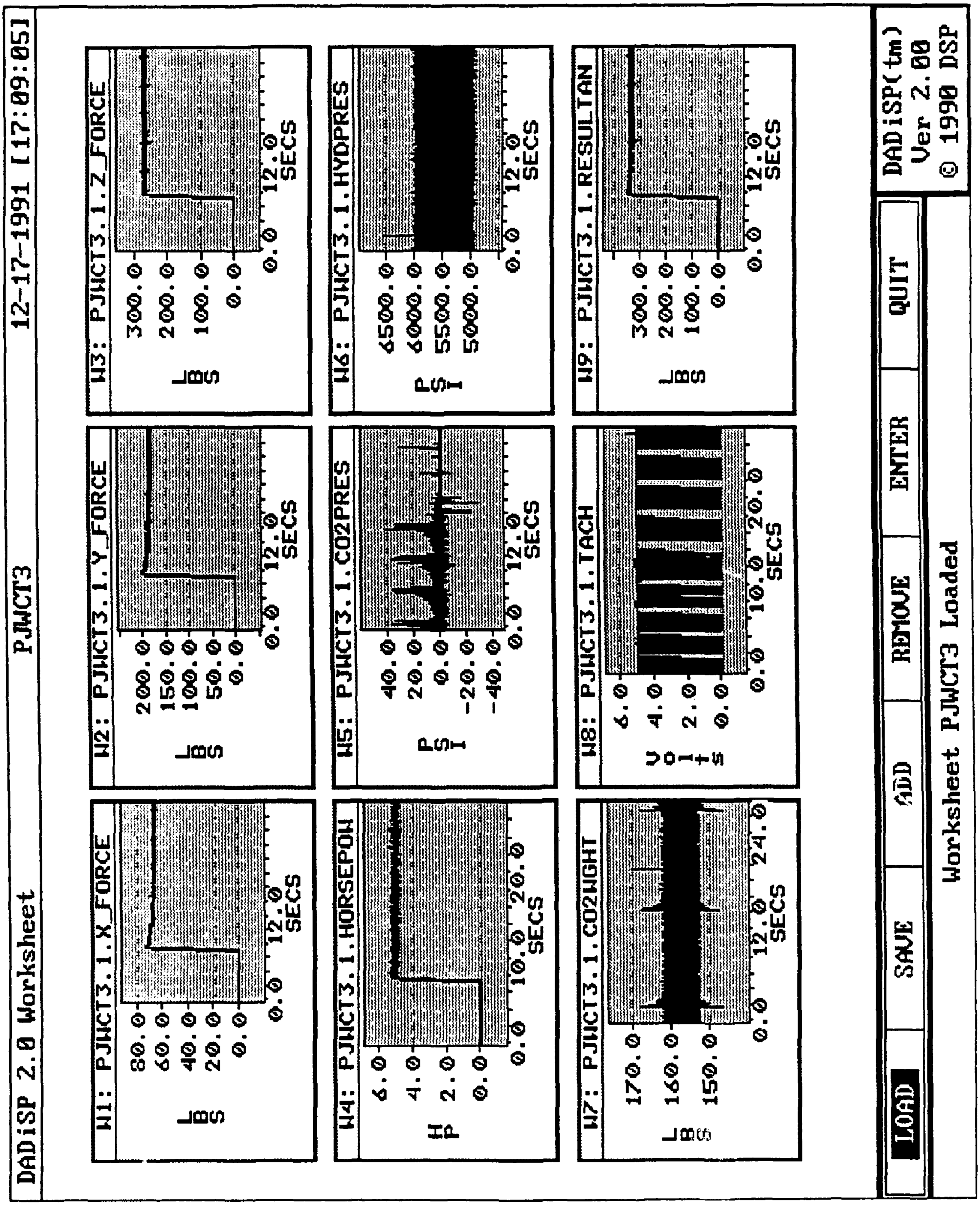
Worksheet PFLDT2 Loaded



DADiSP 2.0 Worksheet
PJWCT3
12-17-1991 [17:09:05]
W1: PJWCT3.1.X_FORCE
W2: PJWCT3.1.Y_FORCE
W3: PJWCT3.1.Z_FORCE
W4: PJWCT3.1.HORSEPOW
W5: PJWCT3.1.CO2PRES
W6: PJWCT3.1.HYDPRES
W7: PJWCT3.1.CO2WGHT
W8: PJWCT3.1.TACH
W9: PJWCT3.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet PJWCT3 Loaded
DADiSP(tm)
Ver 2.00
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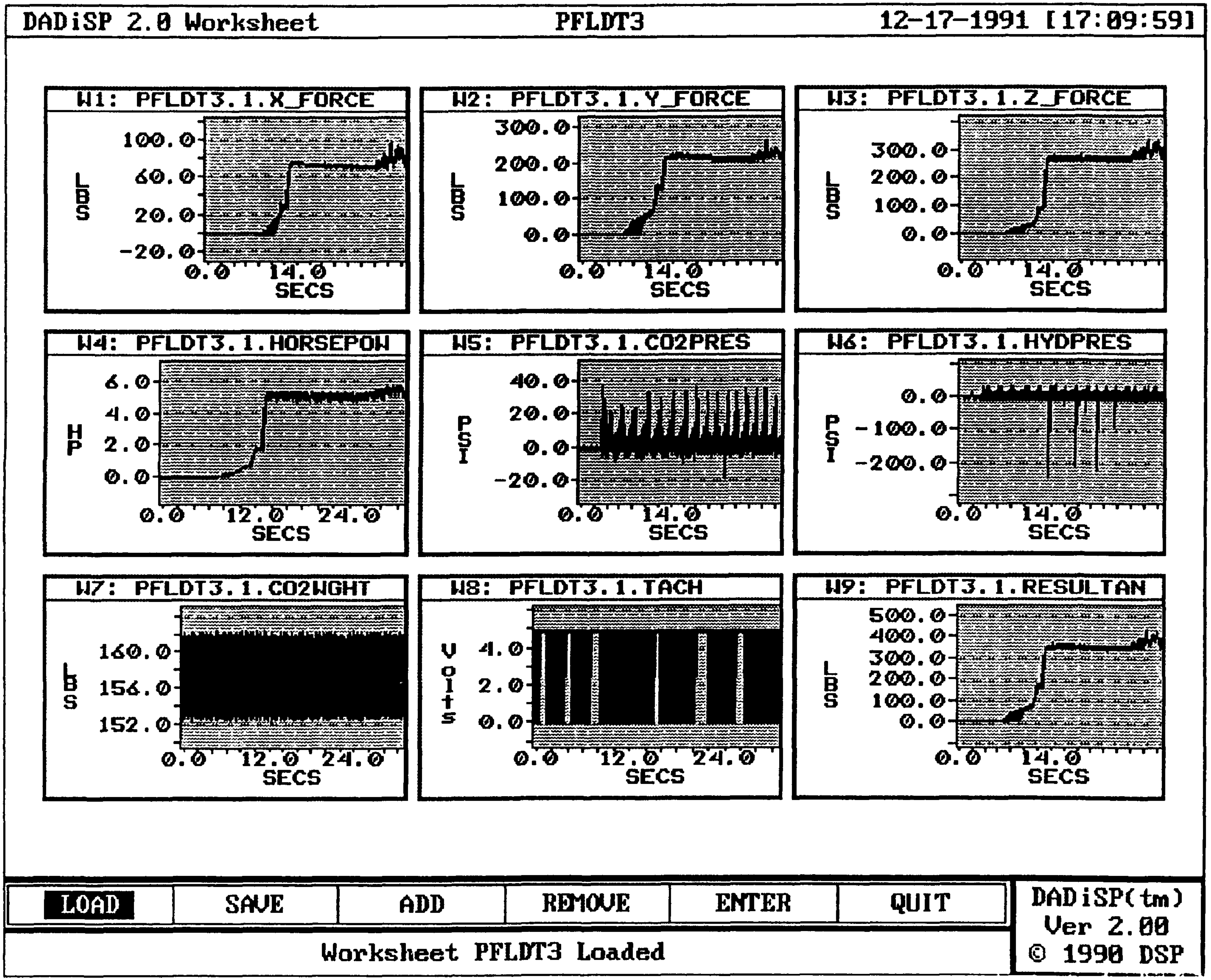
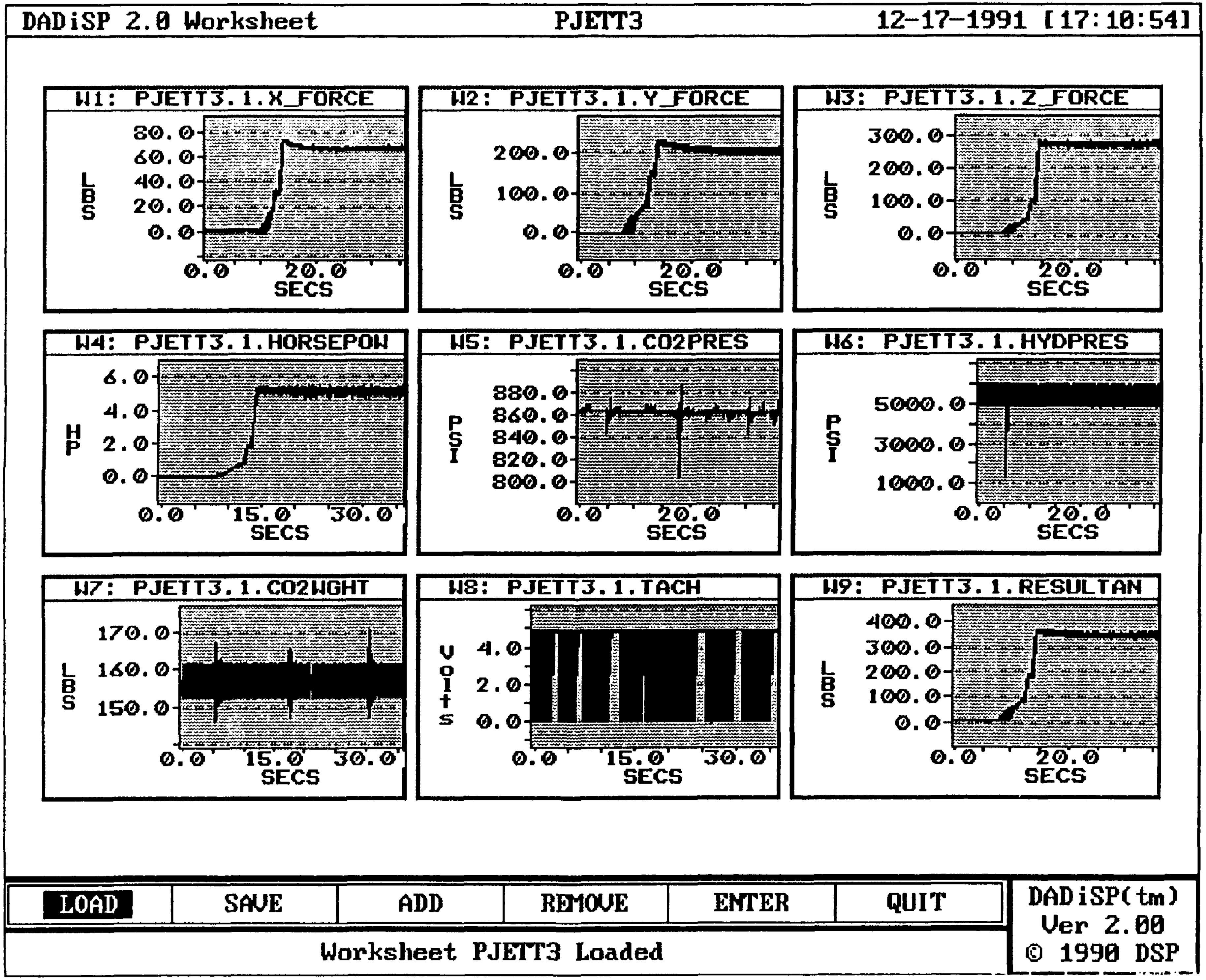

DADiSP 2.0 Worksheet
PFLDT3
12-17-1991 [17:09:59]
W1: PFLDT3.1.X_FORCE
LBS
100.0
60.0
20.0
-20.0
0.0
14.0
SECS
W2: PFLDT3.1.Y_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
14.0
SECS
W3: PFLDT3.1.Z_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
14.0
SECS
W4: PFLDT3.1.HORSEPOW
HP
6.0
4.0
2.0
0.0
0.0
12.0
24.0
SECS
W5: PFLDT3.1.CO2PRES
PSI
40.0
20.0
0.0
-20.0
0.0
14.0
SECS
W6: PFLDT3.1.HYDPRES
PSI
0.0
-100.0
-200.0
0.0
14.0
SECS
W7: PFLDT3.1.CO2WGHT
LBS
160.0
156.0
152.0
0.0
12.0
24.0
SECS
W8: PFLDT3.1.TACH
Volts
4.0
2.0
0.0
0.0
12.0
24.0
SECS
W9: PFLDT3.1.RESULTAN
LBS
500.0
400.0
300.0
200.0
100.0
0.0
0.0
14.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
Ver 2.00
© 1990 DSP
Worksheet PFLDT3 Loaded



DADiSP 2.0 Worksheet
PJETT3
12-17-1991 [17:10:54]
W1: PJETT3.1.X_FORCE
W2: PJETT3.1.Y_FORCE
W3: PJETT3.1.Z_FORCE
W4: PJETT3.1.HORSEPOW
W5: PJETT3.1.CO2PRES
W6: PJETT3.1.HYDPRES
W7: PJETT3.1.CO2WGHT
W8: PJETT3.1.TACH
W9: PJETT3.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet PJETT3 Loaded
DADiSP(tm)
Ver 2.00
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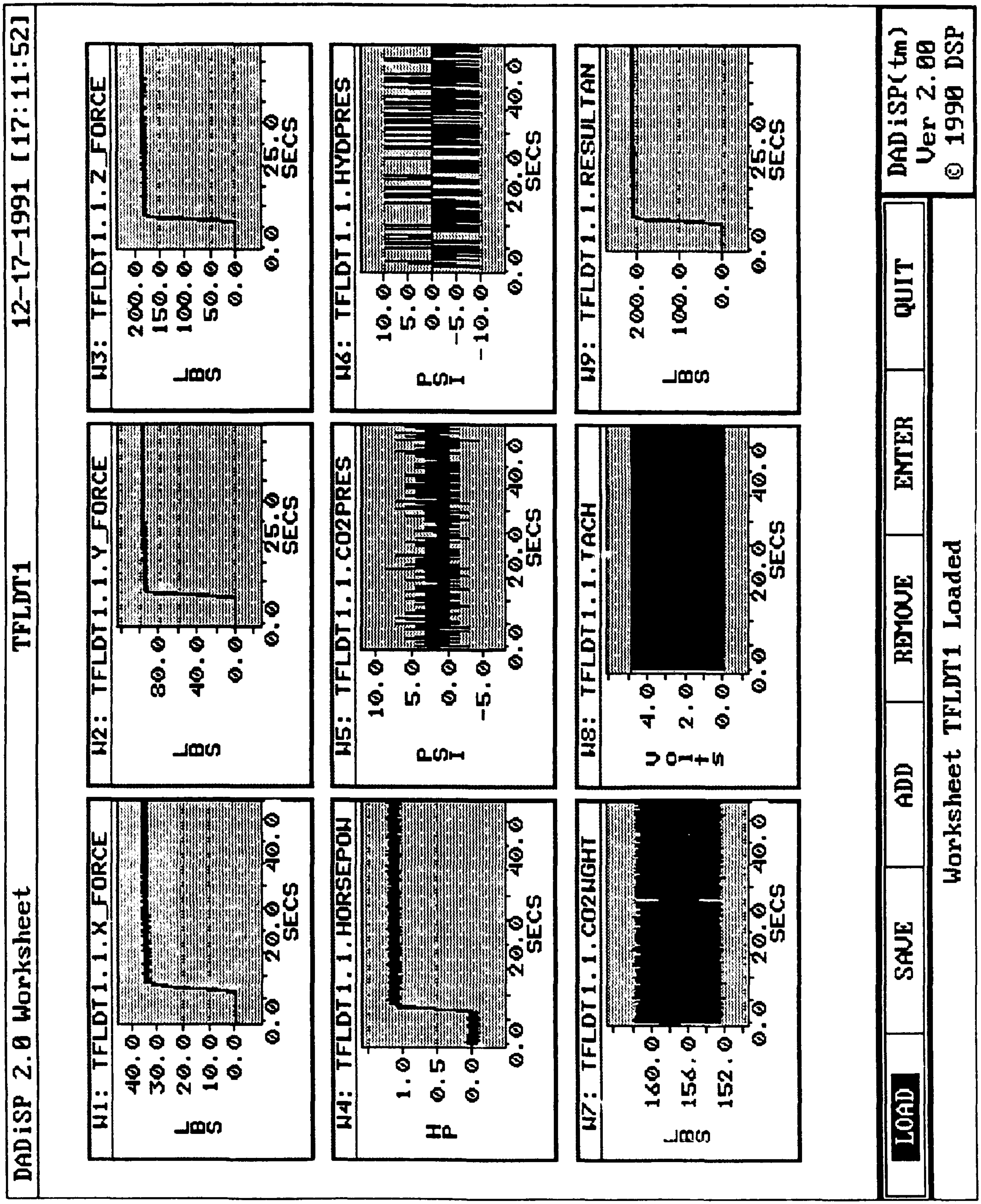
DADiSP 2.0 Worksheet
TFLDT1
12-17-1991 [17:11:52]
W1: TFLDT1.1.X_FORCE
W2: TFLDT1.1.Y_FORCE
W3: TFLDT1.1.Z_FORCE
W4: TFLDT1.1.HORSEPOW
W5: TFLDT1.1.CO2PRES
W6: TFLDT1.1.HYDPRES
W7: TFLDT1.1.CO2WGHT
W8: TFLDT1.1.TACH
W9: TFLDT1.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet TFLDT1 Loaded
DADiSP(tm)
Ver 2.00
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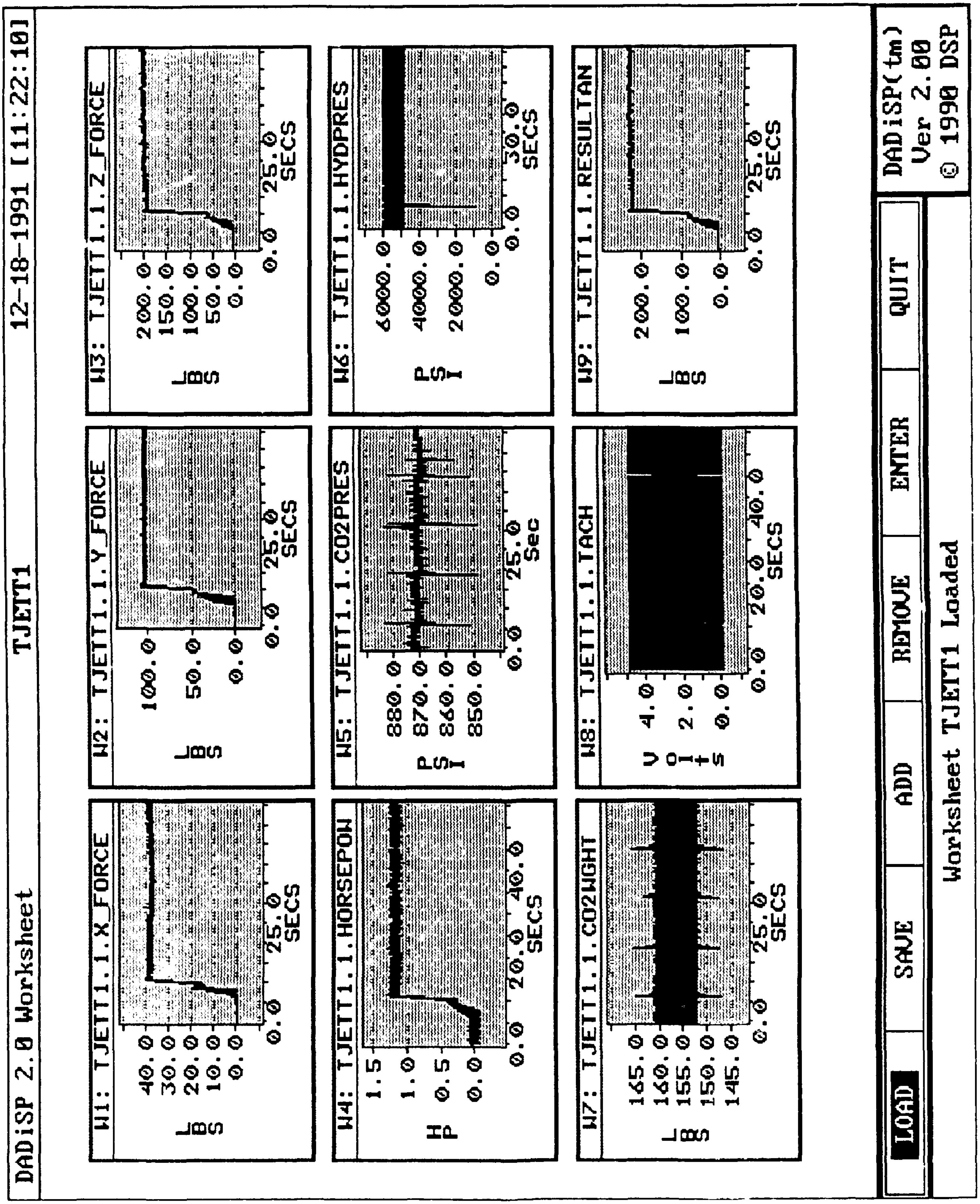
DADiSP 2.0 Worksheet
TJETT1
12-18-1991 [11:22:10]
W1: TJETT1.1.X_FORCE
LBS
40.0
30.0
20.0
10.0
0.0
0.0
25.0
SECS
W2: TJETT1.1.Y_FORCE
LBS
100.0
50.0
0.0
0.0
25.0
SECS
W3: TJETT1.1.Z_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
25.0
SECS
W4: TJETT1.1.HORSEPOW
HP
1.5
1.0
0.5
0.0
0.0
20.0
40.0
SECS
W5: TJETT1.1.CO2PRES
PSI
880.0
870.0
860.0
850.0
0.0
25.0
Sec
W6: TJETT1.1.HYDPRES
PSI
6000.0
4000.0
2000.0
0.0
0.0
30.0
SECS
W7: TJETT1.1.CO2WGHT
LBS
165.0
160.0
155.0
150.0
145.0
0.0
25.0
SECS
W8: TJETT1.1.TACH
Volts
4.0
2.0
0.0
0.0
20.0
40.0
SECS
W9: TJETT1.1.RESULTAN
LBS
200.0
100.0
0.0
0.0
25.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
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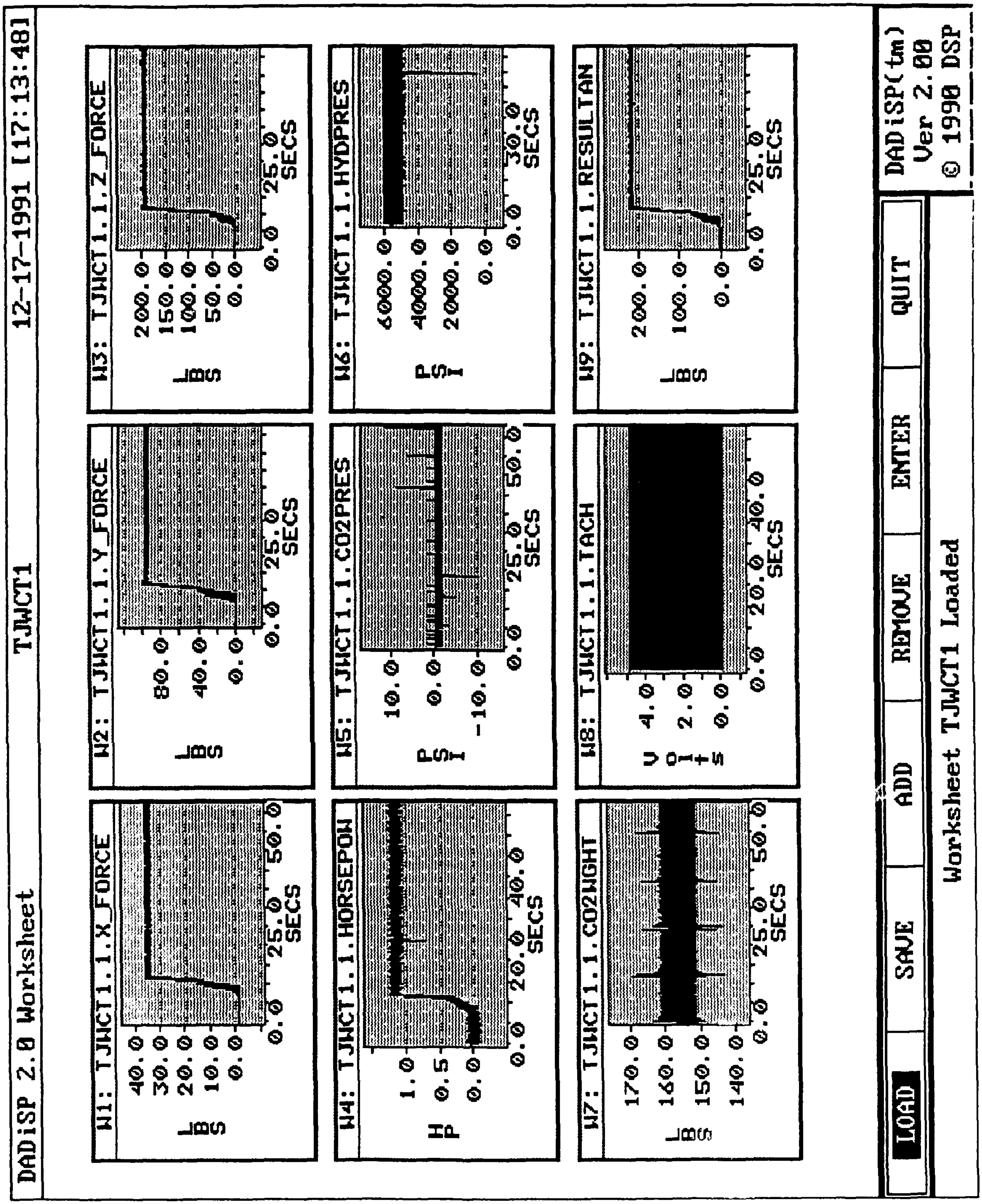
Worksheet TJETT1 Loaded


DADiSP 2.0 Worksheet
TJWCT1
12-17-1991 [17:13:48]
W1: TJWCT1.1.X_FORCE
W2: TJWCT1.1.Y_FORCE
W3: TJWCT1.1.Z_FORCE
W4: TJWCT1.1.HORSEPOW
W5: TJWCT1.1.CO2PRES
W6: TJWCT1.1.HYDPRES
W7: TJWCT1.1.CO2WGHT
W8: TJWCT1.1.TACH
W9: TJWCT1.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet TJWCT1 Loaded
DADiSP(tm)
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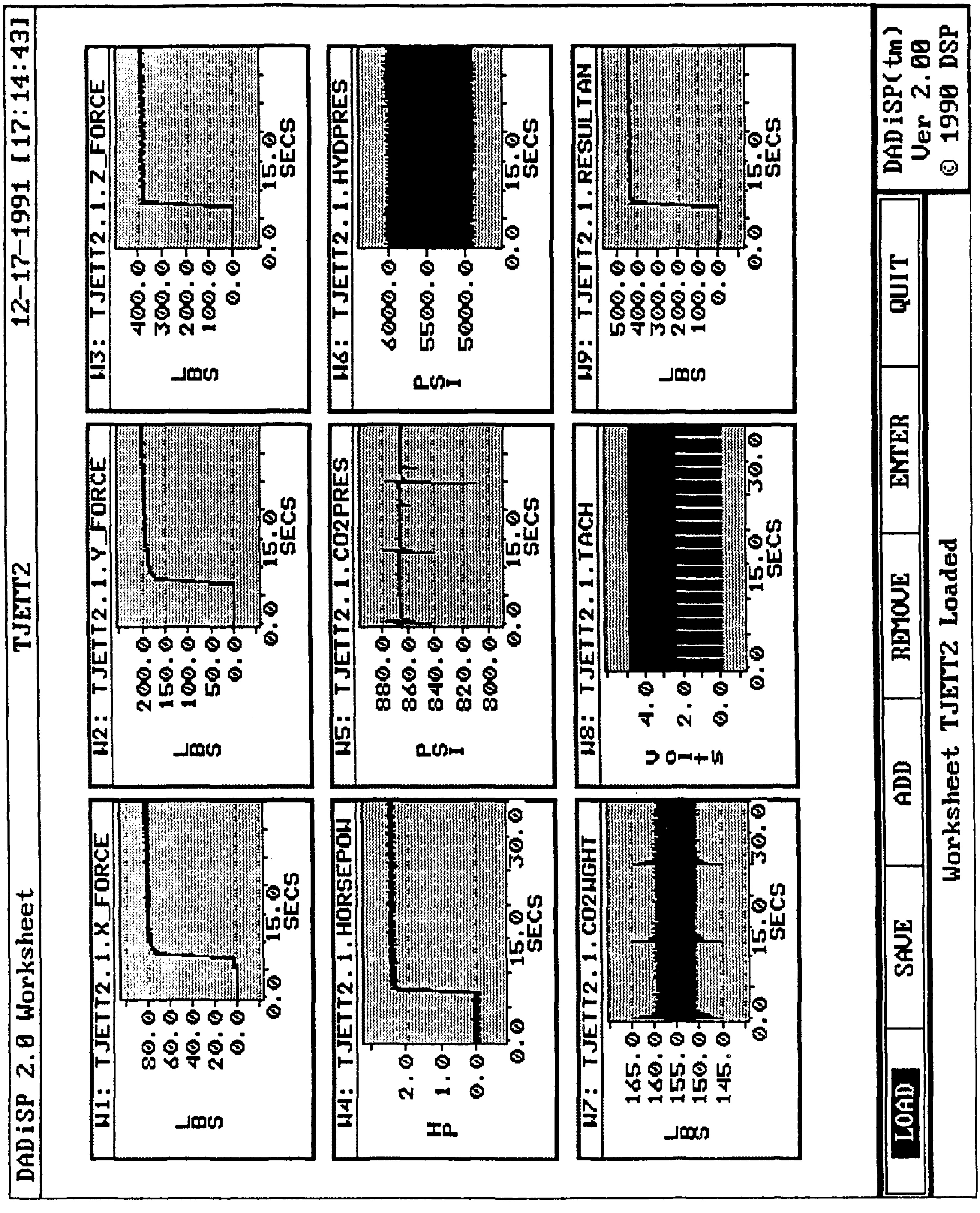
DADiSP 2.0 Worksheet
TJETT2
12-17-1991 [17:14:43]
W1: TJETT2.1.X_FORCE
W2: TJETT2.1.Y_FORCE
W3: TJETT2.1.Z_FORCE
W4: TJETT2.1.HORSEPOW
W5: TJETT2.1.CO2PRES
W6: TJETT2.1.HYDPRES
W7: TJETT2.1.CO2WGHT
W8: TJETT2.1.TACH
W9: TJETT2.1.RESULTAN
LBS
HP
PSI
VOLTS
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet TJETT2 Loaded
DADiSP(tm)
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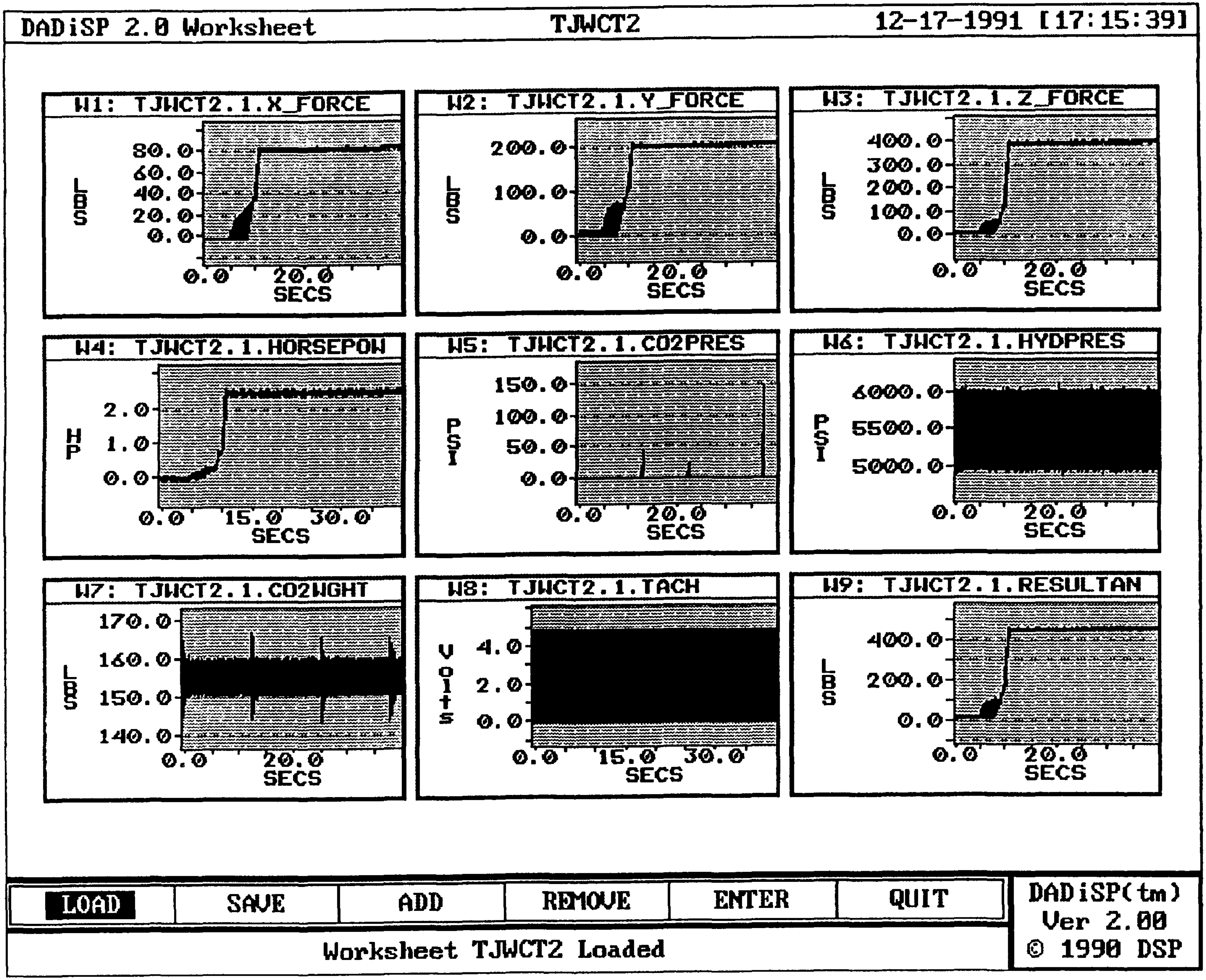

DADiSP 2.0 Worksheet
TJWCT2
12-17-1991 [17:15:39]
W1: TJWCT2.1.X_FORCE
LBS
80.0
60.0
40.0
20.0
0.0
0.0
20.0
SECS
W2: TJWCT2.1.Y_FORCE
LBS
200.0
100.0
0.0
0.0
20.0
SECS
W3: TJWCT2.1.Z_FORCE
LBS
400.0
300.0
200.0
100.0
0.0
0.0
20.0
SECS
W4: TJWCT2.1.HORSEPOW
HP
2.0
1.0
0.0
0.0
15.0
30.0
SECS
W5: TJWCT2.1.CO2PRES
PSI
150.0
100.0
50.0
0.0
0.0
20.0
SECS
W6: TJWCT2.1.HYDPRES
PSI
6000.0
5500.0
5000.0
0.0
20.0
SECS
W7: TJWCT2.1.CO2WGHT
LBS
170.0
160.0
150.0
140.0
0.0
20.0
SECS
W8: TJWCT2.1.TACH
Volts
4.0
2.0
0.0
0.0
15.0
30.0
SECS
W9: TJWCT2.1.RESULTAN
LBS
400.0
200.0
0.0
0.0
20.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
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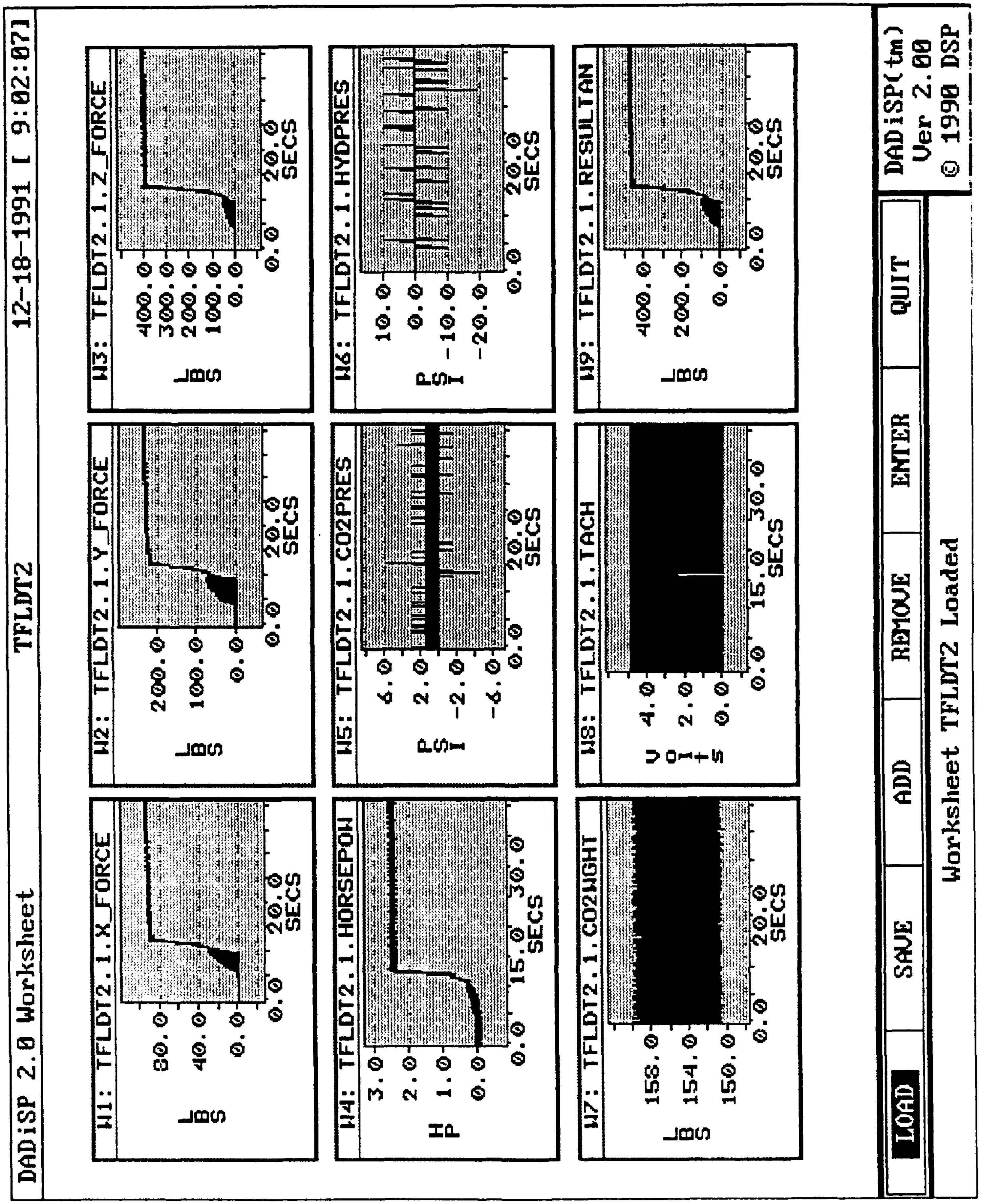
Worksheet TJWCT2 Loaded


DADiSP 2.0 Worksheet
TFLDT2
12-18-1991 [9:02:07]
W1: TFLDT2.1.X_FORCE
W2: TFLDT2.1.Y_FORCE
W3: TFLDT2.1.Z_FORCE
W4: TFLDT2.1.HORSEPOW
W5: TFLDT2.1.CO2PRES
W6: TFLDT2.1.HYDPRES
W7: TFLDT2.1.CO2WGHT
W8: TFLDT2.1.TACH
W9: TFLDT2.1.RESULTAN
LBS
HP
PSI
VOLTS
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet TFLDT2 Loaded
DADiSP(tm)
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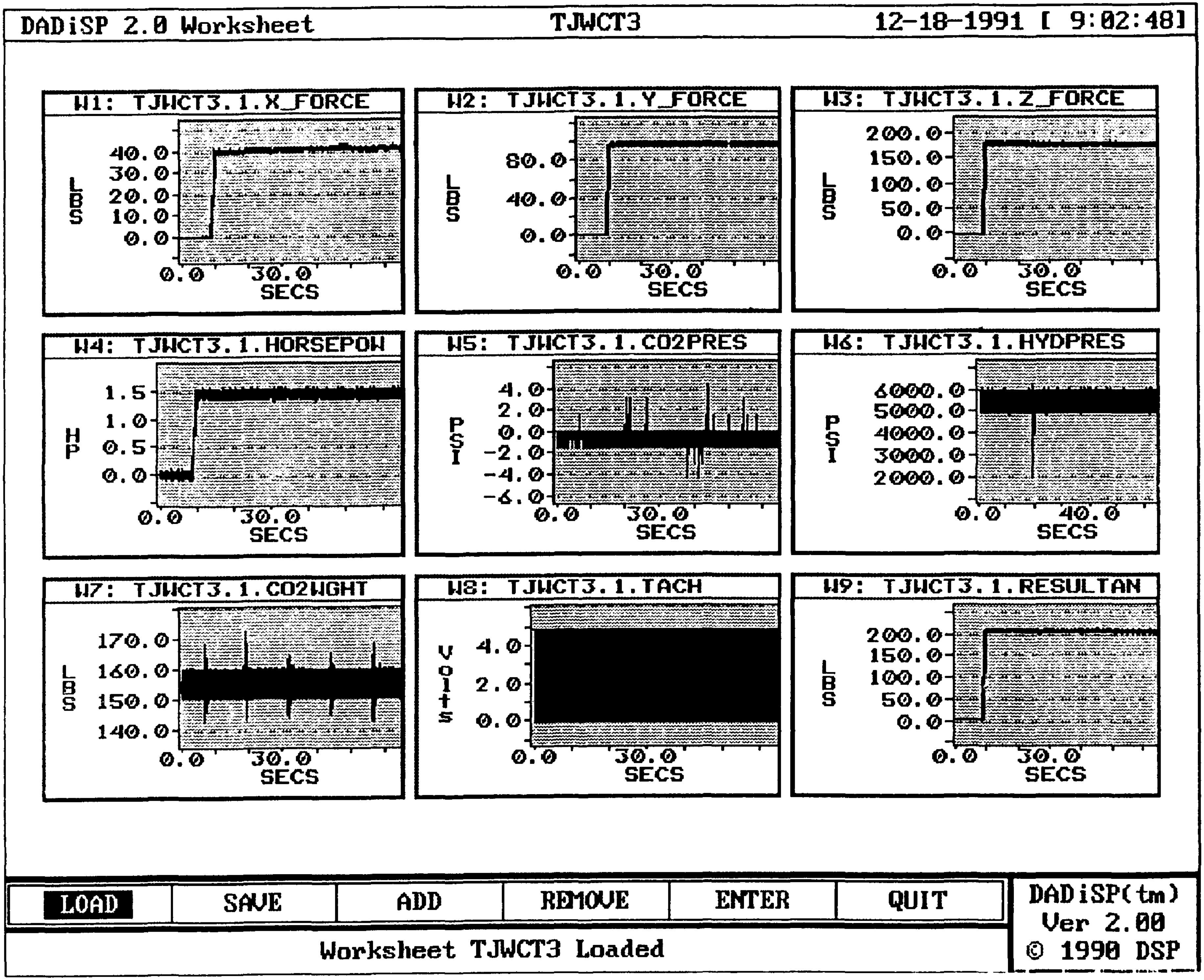
DADiSP 2.0 Worksheet
TJWCT3
12-18-1991 [9:02:48]
W1: TJWCT3.1.X_FORCE
LBS
40.0
30.0
20.0
10.0
0.0
0.0
30.0
SECS
W2: TJWCT3.1.Y_FORCE
LBS
80.0
40.0
0.0
0.0
30.0
SECS
W3: TJWCT3.1.Z_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
30.0
SECS
W4: TJWCT3.1.HORSEPOW
HP
1.5
1.0
0.5
0.0
0.0
30.0
SECS
W5: TJWCT3.1.CO2PRES
PSI
4.0
2.0
0.0
-2.0
-4.0
-6.0
0.0
30.0
SECS
W6: TJWCT3.1.HYDPRES
PSI
6000.0
5000.0
4000.0
3000.0
2000.0
0.0
40.0
SECS
W7: TJWCT3.1.CO2WGHT
LBS
170.0
160.0
150.0
140.0
0.0
30.0
SECS
W8: TJWCT3.1.TACH
Volts
4.0
2.0
0.0
0.0
30.0
SECS
W9: TJWCT3.1.RESULTAN
LBS
200.0
150.0
100.0
50.0
0.0
0.0
30.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
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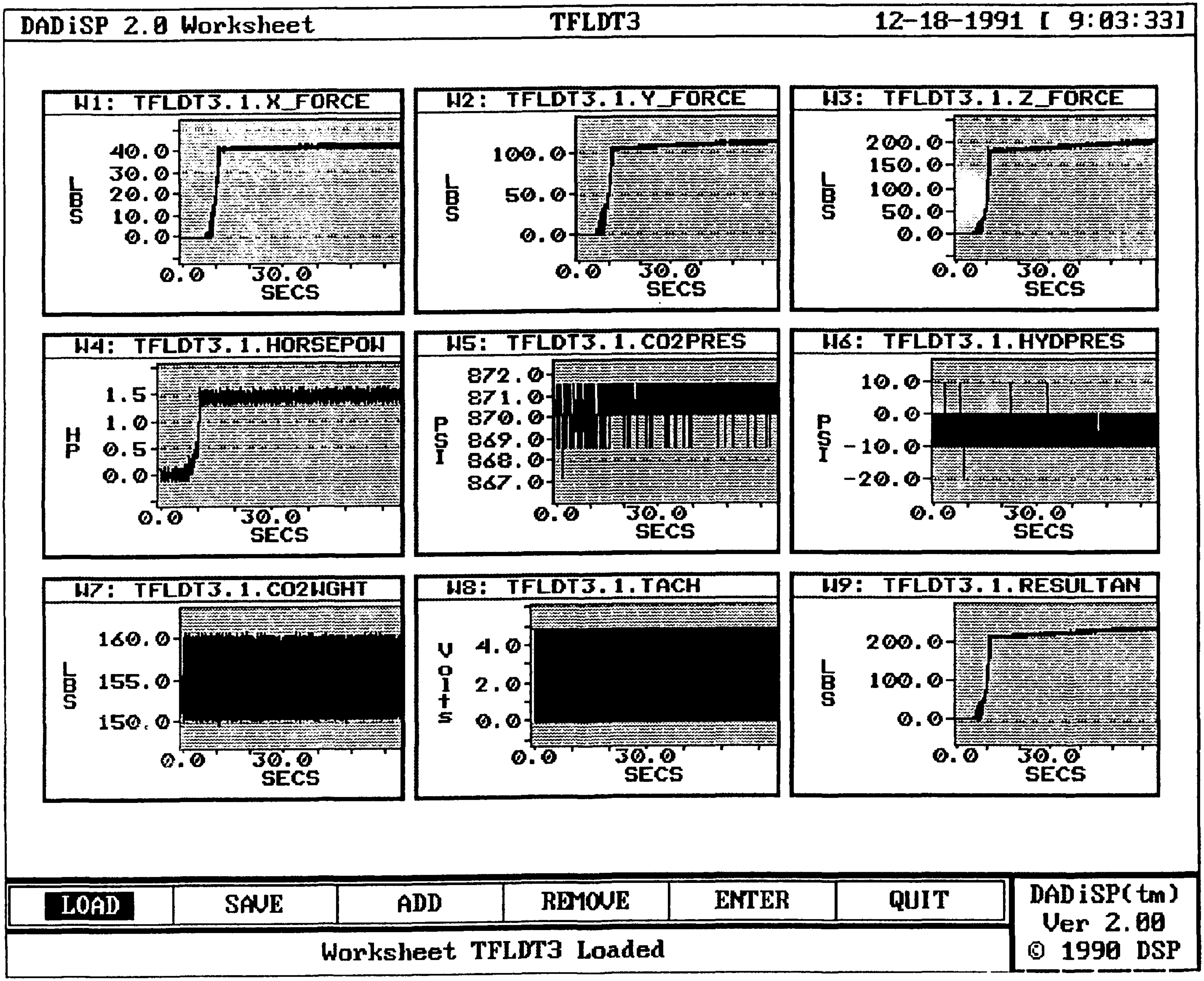
Worksheet TJWCT3 Loaded


DADiSP 2.0 Worksheet
TFLDT3
12-18-1991 [9:03:33]
W1: TFLDT3.1.X_FORCE
LBS
40.0
30.0
20.0
10.0
0.0
0.0
30.0
SECS
W2: TFLDT3.1.Y_FORCE
LBS
100.0
50.0
0.0
0.0
30.0
SECS
W3: TFLDT3.1.Z_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
30.0
SECS
W4: TFLDT3.1.HORSEPOW
HP
1.5
1.0
0.5
0.0
0.0
30.0
SECS
W5: TFLDT3.1.CO2PRES
PSI
872.0
871.0
870.0
869.0
868.0
867.0
0.0
30.0
SECS
W6: TFLDT3.1.HYDPRES
PSI
10.0
0.0
-10.0
-20.0
0.0
30.0
SECS
W7: TFLDT3.1.CO2WGHT
LBS
160.0
155.0
150.0
0.0
30.0
SECS
W8: TFLDT3.1.TACH
Volts
4.0
2.0
0.0
0.0
30.0
SECS
W9: TFLDT3.1.RESULTAN
LBS
200.0
100.0
0.0
0.0
30.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet TFLDT3 Loaded
DADiSP(tm)
Ver 2.00
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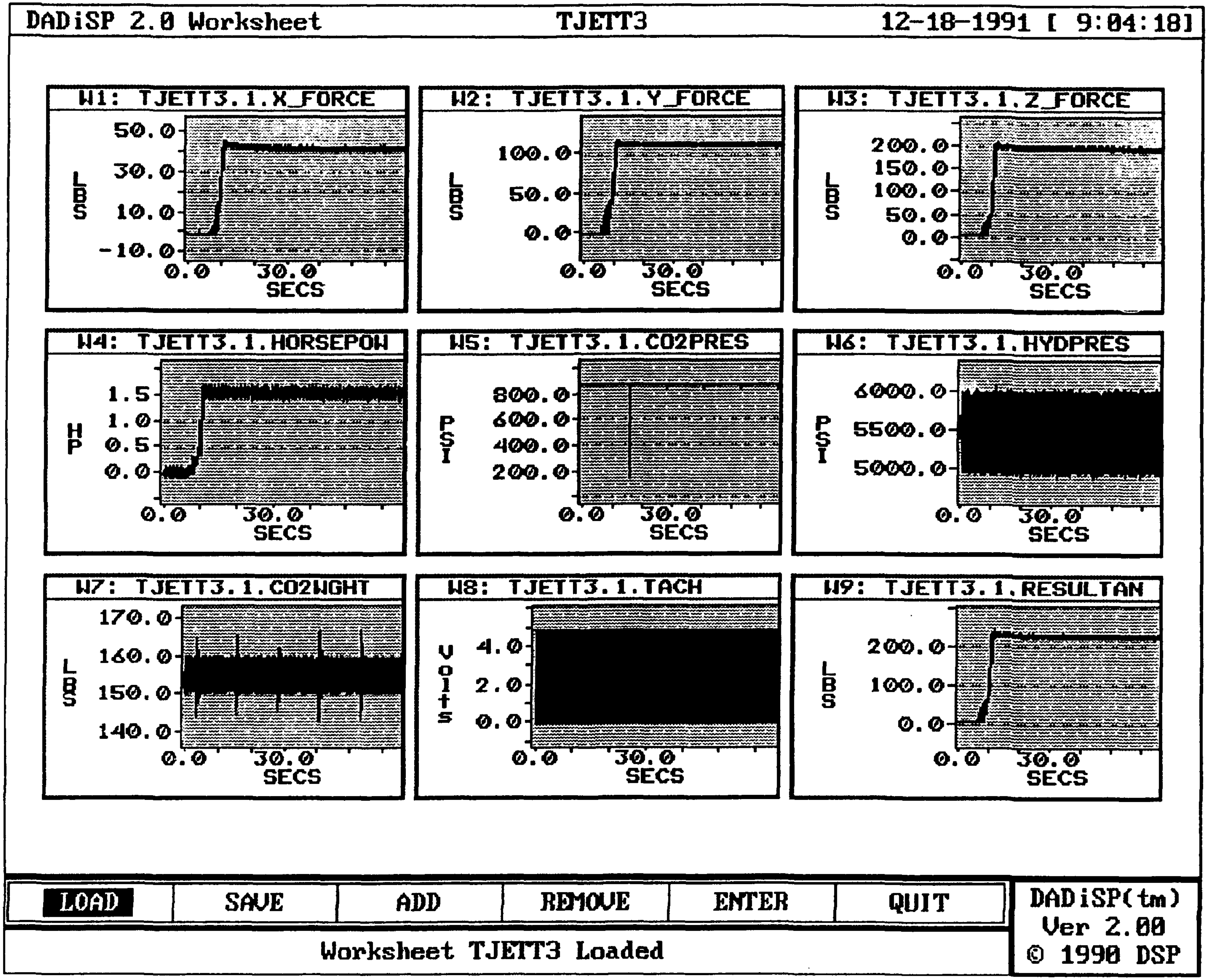
DADiSP 2.0 Worksheet
TJETT3
12-18-1991 [9:04:18]
W1: TJETT3.1.X_FORCE
LBS
50.0
30.0
10.0
-10.0
0.0
30.0
SECS
W2: TJETT3.1.Y_FORCE
LBS
100.0
50.0
0.0
0.0
30.0
SECS
W3: TJETT3.1.Z_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
30.0
SECS
W4: TJETT3.1.HORSEPOW
HP
1.5
1.0
0.5
0.0
0.0
30.0
SECS
W5: TJETT3.1.CO2PRES
PSI
800.0
600.0
400.0
200.0
0.0
30.0
SECS
W6: TJETT3.1.HYDPRES
PSI
6000.0
5500.0
5000.0
0.0
30.0
SECS
W7: TJETT3.1.CO2WGHT
LBS
170.0
160.0
150.0
140.0
0.0
30.0
SECS
W8: TJETT3.1.TACH
Volts
4.0
2.0
0.0
0.0
30.0
SECS
W9: TJETT3.1.RESULTAN
LBS
200.0
100.0
0.0
0.0
30.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
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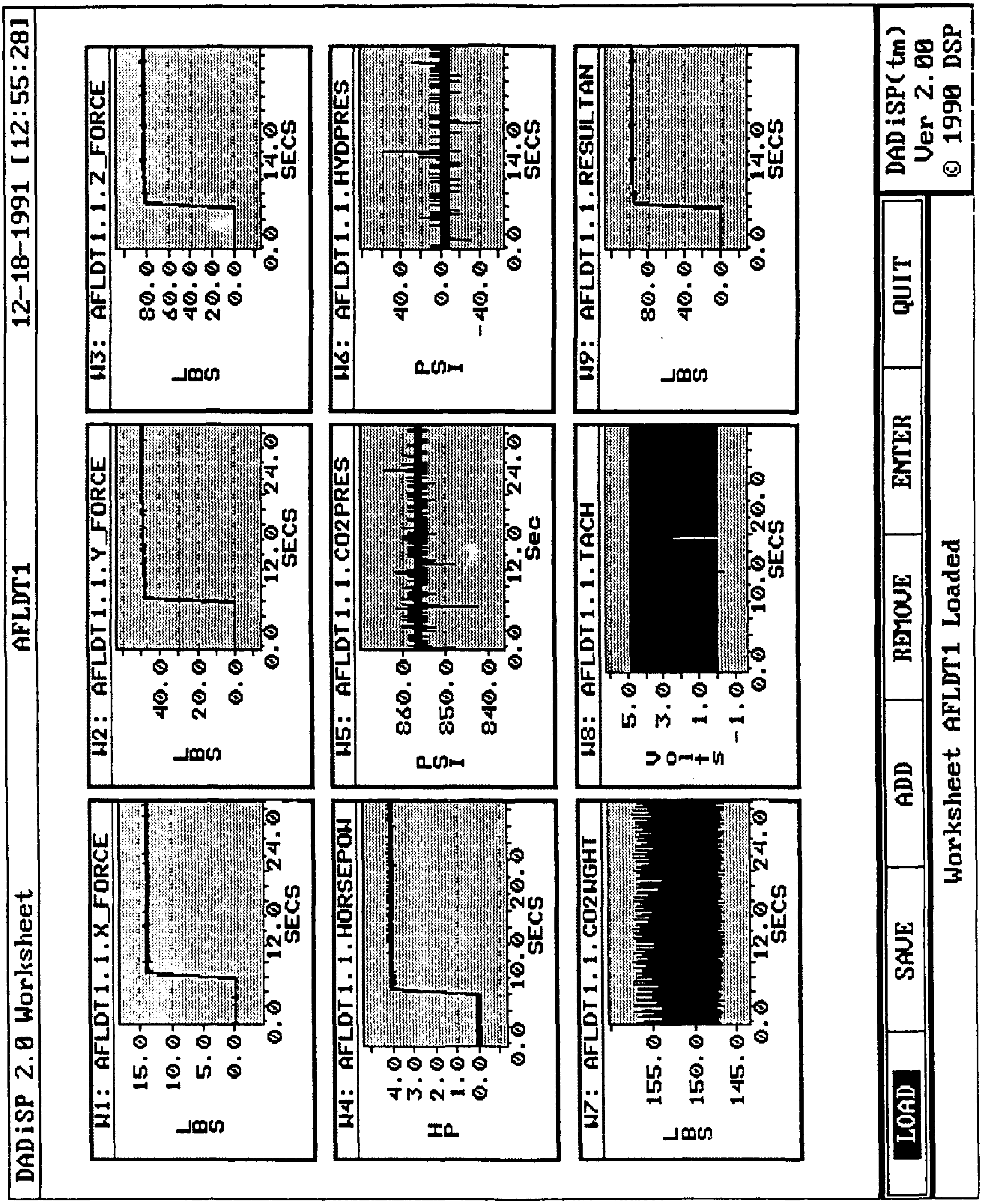
Worksheet TJETT3 Loaded


DADiSP 2.0 Worksheet
AFLDT1
12-18-1991 [12:55:28]
W1: AFLDT1.1.X_FORCE
LBS
SECS
W2: AFLDT1.1.Y_FORCE
LBS
SECS
W3: AFLDT1.1.Z_FORCE
LBS
SECS
W4: AFLDT1.1.HORSEPOW
HP
SECS
W5: AFLDT1.1.CO2PRES
PSI
Sec
W6: AFLDT1.1.HYDPRES
PSI
SECS
W7: AFLDT1.1.CO2WGHT
LBS
SECS
W8: AFLDT1.1.TACH
Volts
SECS
W9: AFLDT1.1.RESULTAN
LBS
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet AFLDT1 Loaded
DADiSP(tm)
Ver 2.00
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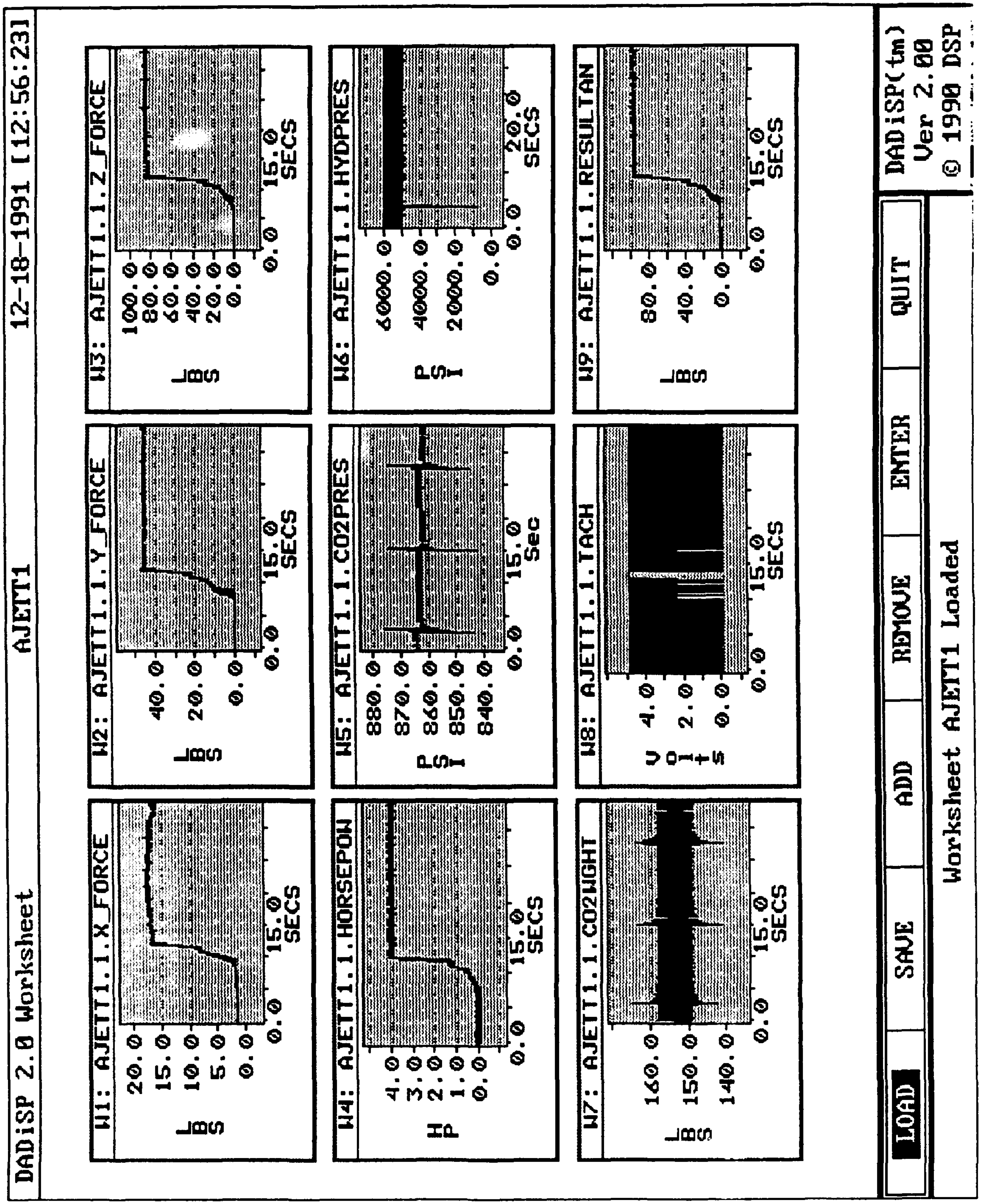
DADiSP 2.0 Worksheet
AJETT1
12-18-1991 [12:56:23]
W1: AJETT1.1.1.X_FORCE
LBS
SECS
W2: AJETT1.1.1.Y_FORCE
LBS
SECS
W3: AJETT1.1.1.Z_FORCE
LBS
SECS
W4: AJETT1.1.1.HORSEPOW
HP
SECS
W5: AJETT1.1.1.CO2PRES
PSI
Sec
W6: AJETT1.1.1.HYDPRES
PSI
SECS
W7: AJETT1.1.1.CO2WGHT
LBS
SECS
W8: AJETT1.1.1.TACH
Volts
SECS
W9: AJETT1.1.1.RESULTAN
LBS
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet AJETT1 Loaded
DADiSP(tm)
Ver 2.00
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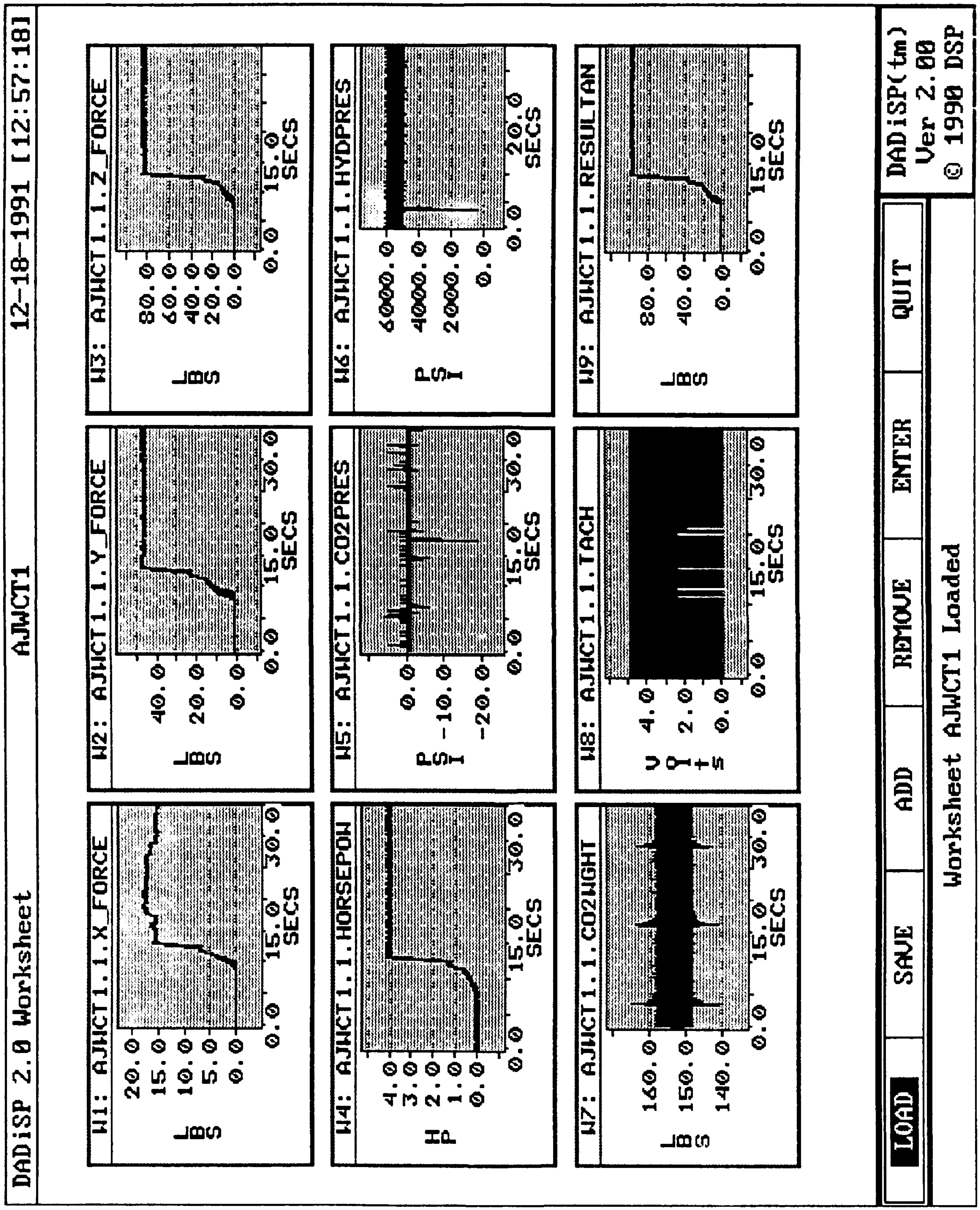
DADiSP 2.0 Worksheet
AJWCT1
12-18-1991 [12:57:18]
W1: AJWCT1.1.X_FORCE
W2: AJWCT1.1.Y_FORCE
W3: AJWCT1.1.Z_FORCE
W4: AJWCT1.1.HORSEPOW
W5: AJWCT1.1.CO2PRES
W6: AJWCT1.1.HYDPRES
W7: AJWCT1.1.CO2WGHT
W8: AJWCT1.1.TACH
W9: AJWCT1.1.RESULTAN
LBS
HP
PSI
VOLTS
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet AJWCT1 Loaded
DADiSP(tm)
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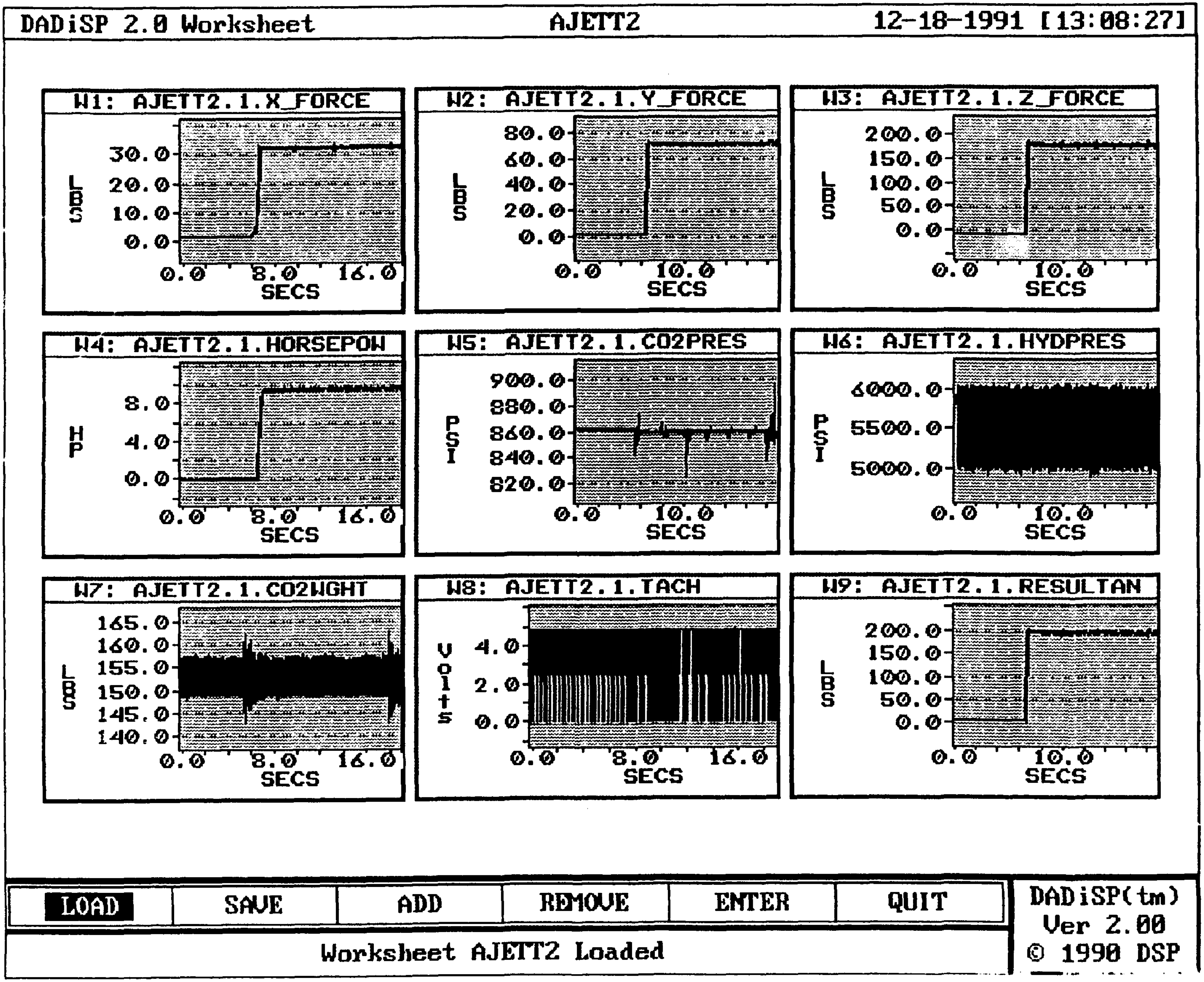

DADiSP 2.0 Worksheet
AJETT2
12-18-1991 [13:08:27]
W1: AJETT2.1.X_FORCE
LBS
30.0
20.0
10.0
0.0
0.0
8.0
16.0
SECS
W2: AJETT2.1.Y_FORCE
LBS
80.0
60.0
40.0
20.0
0.0
0.0
10.0
SECS
W3: AJETT2.1.Z_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
10.0
SECS
W4: AJETT2.1.HORSEPOW
HP
8.0
4.0
0.0
0.0
8.0
16.0
SECS
W5: AJETT2.1.CO2PRES
PSI
900.0
880.0
860.0
840.0
820.0
0.0
10.0
SECS
W6: AJETT2.1.HYDPRES
PSI
6000.0
5500.0
5000.0
0.0
10.0
SECS
W7: AJETT2.1.CO2WGHT
LBS
165.0
160.0
155.0
150.0
145.0
140.0
0.0
8.0
16.0
SECS
W8: AJETT2.1.TACH
Volts
4.0
2.0
0.0
0.0
8.0
16.0
SECS
W9: AJETT2.1.RESULTAN
LBS
200.0
150.0
100.0
50.0
0.0
0.0
10.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
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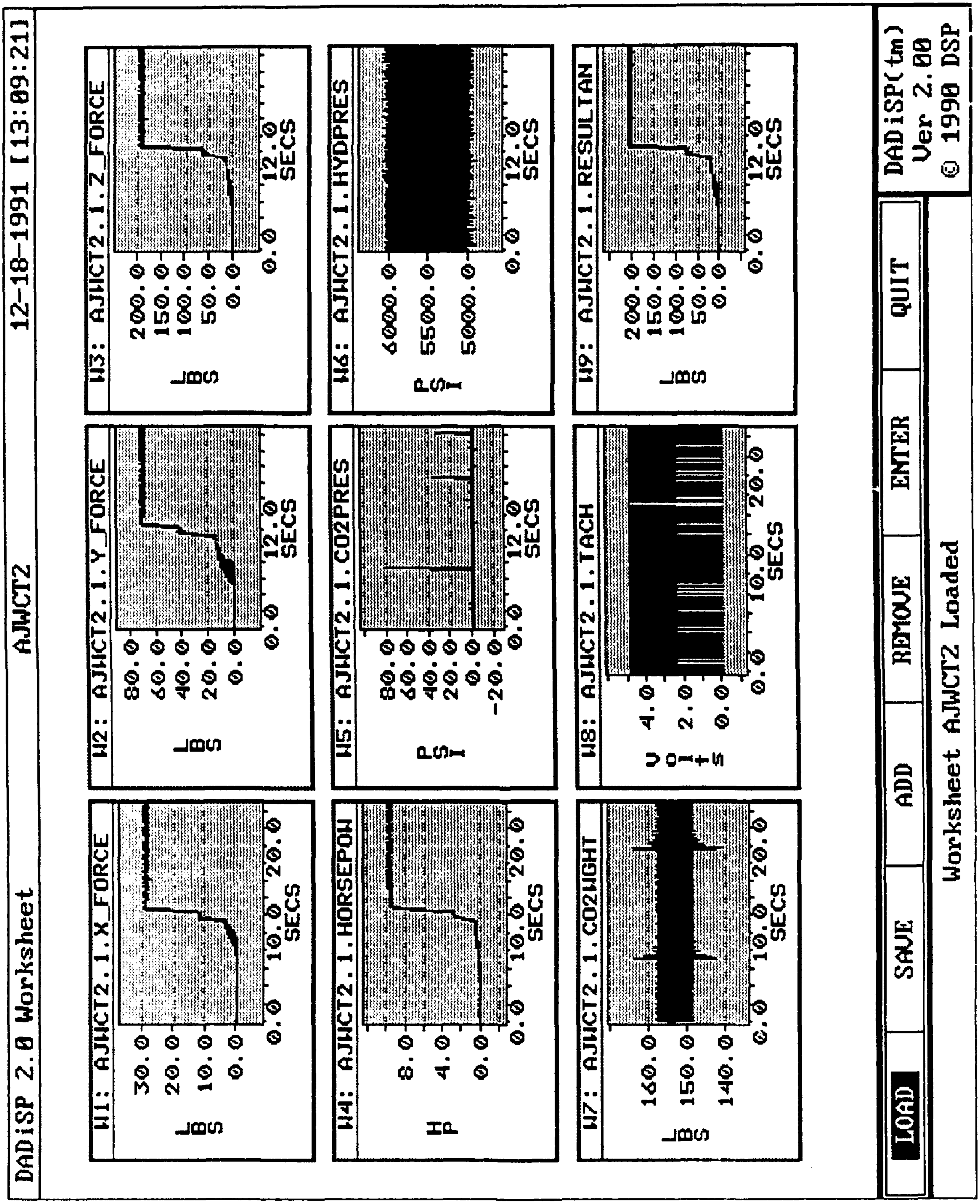
Worksheet AJETT2 Loaded


DADiSP 2.0 Worksheet
AJWCT2
12-18-1991 [13:09:21]
W1: AJWCT2.1.X_FORCE
W2: AJWCT2.1.Y_FORCE
W3: AJWCT2.1.Z_FORCE
W4: AJWCT2.1.HORSEPOW
W5: AJWCT2.1.CO2PRES
W6: AJWCT2.1.HYDPRES
W7: AJWCT2.1.CO2WGHT
W8: AJWCT2.1.TACH
W9: AJWCT2.1.RESULTAN
LBS
HP
PSI
VOLTS
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet AJWCT2 Loaded
DADiSP(tm)
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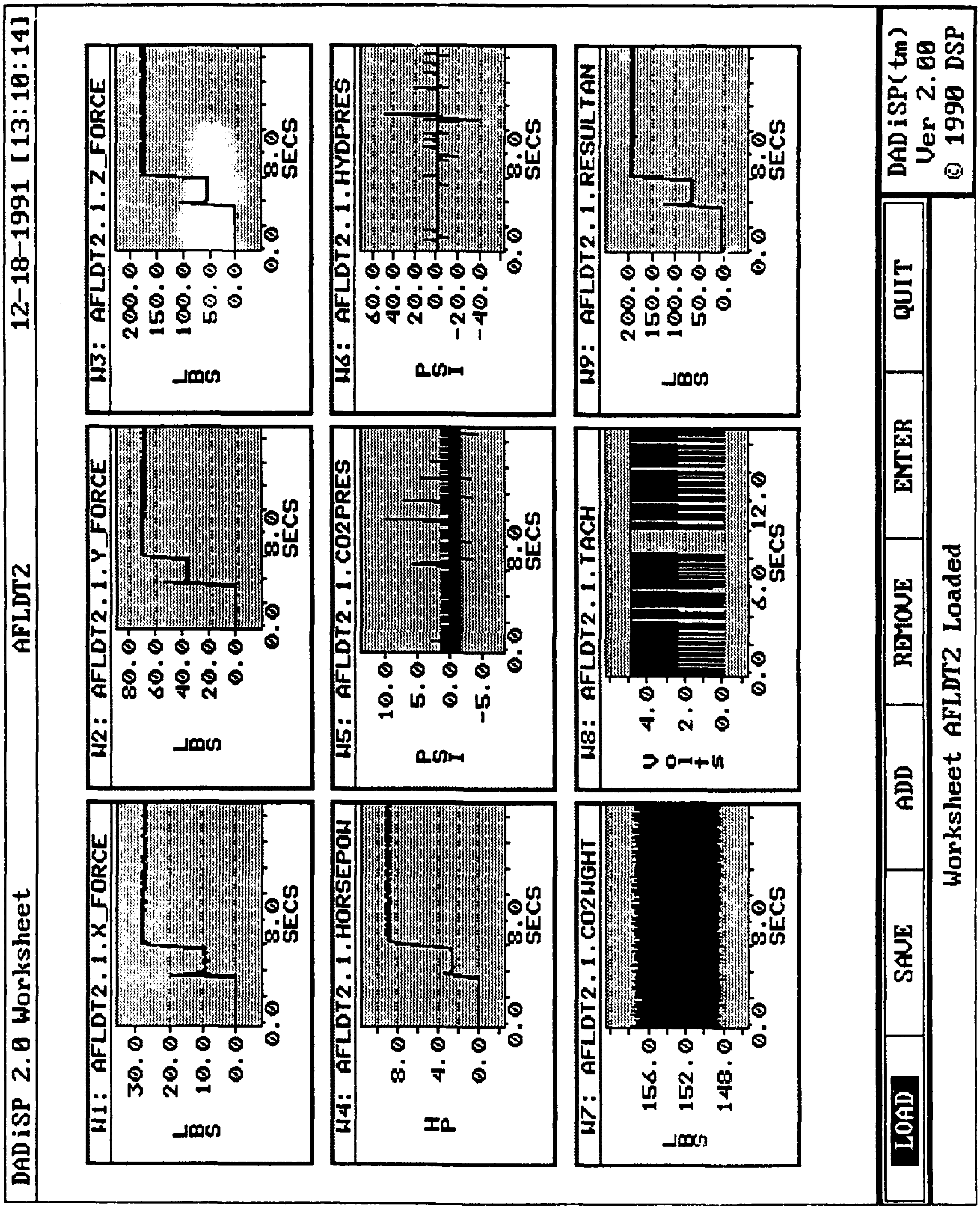
DADiSP 2.0 Worksheet
AFLDT2
12-18-1991 [13:10:14]
W1: AFLDT2.1.X_FORCE
W2: AFLDT2.1.Y_FORCE
W3: AFLDT2.1.Z_FORCE
W4: AFLDT2.1.HORSEPOW
W5: AFLDT2.1.CO2PRES
W6: AFLDT2.1.HYDPRES
W7: AFLDT2.1.CO2WGHT
W8: AFLDT2.1.TACH
W9: AFLDT2.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet AFLDT2 Loaded
DADiSP(tm)
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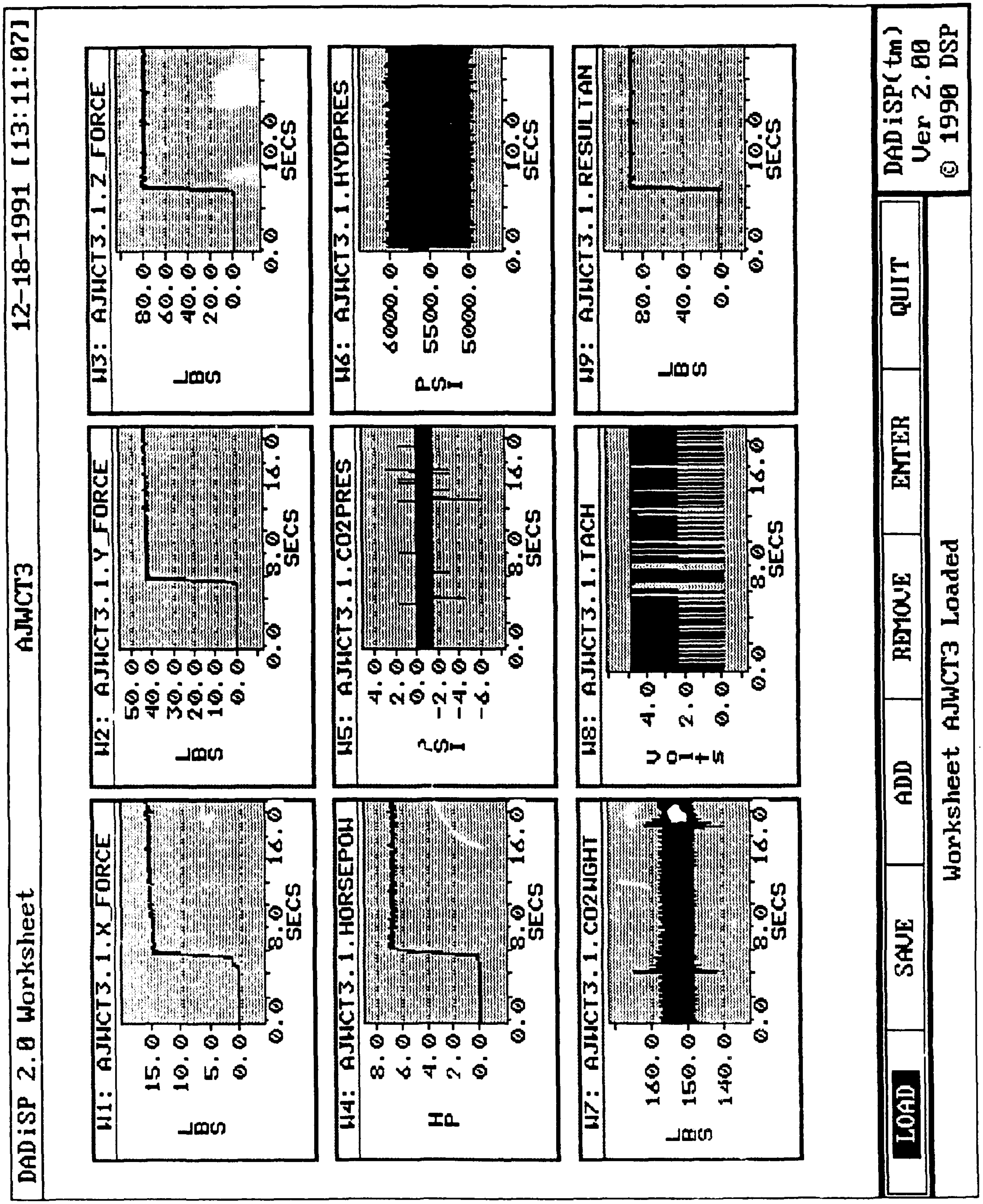
DADiSP 2.0 Worksheet
AJWCT3
12-18-1991 [13:11:07]
W1: AJWCT3.1.X_FORCE
LBS
W2: AJWCT3.1.Y_FORCE
LBS
W3: AJWCT3.1.Z_FORCE
LBS
W4: AJWCT3.1.HORSEPOW
HP
W5: AJWCT3.1.CO2PRES
PSI
W6: AJWCT3.1.HYDPRES
PSI
W7: AJWCT3.1.CO2WGHT
LBS
W8: AJWCT3.1.TACH
Volts
W9: AJWCT3.1.RESULTAN
LBS
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet AJWCT3 Loaded
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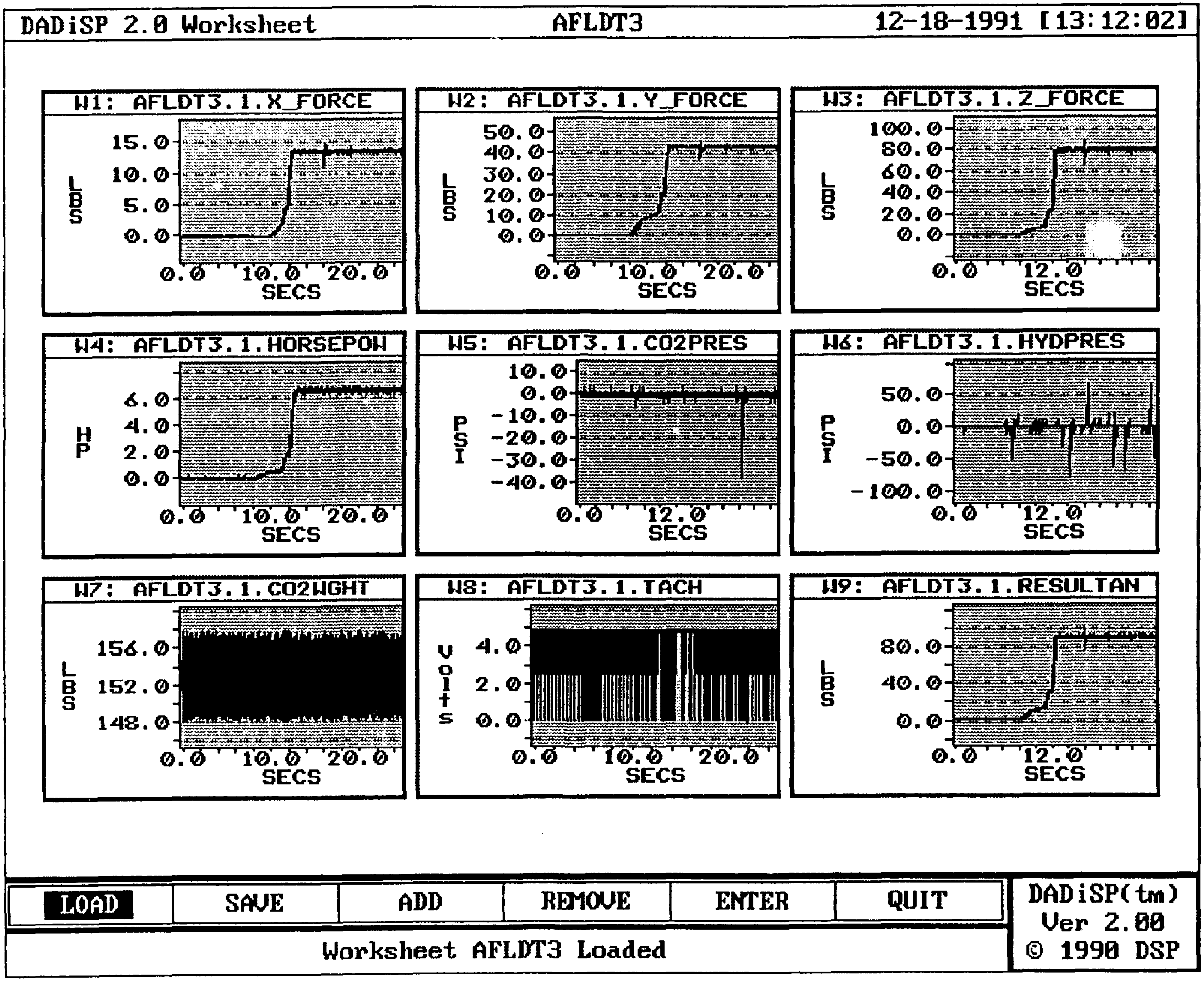
DADiSP 2.0 Worksheet
AFLDT3
12-18-1991 [13:12:02]
W1: AFLDT3.1.X_FORCE
LBS
15.0
10.0
5.0
0.0
0.0 10.0 20.0
SECS
W2: AFLDT3.1.Y_FORCE
LBS
50.0
40.0
30.0
20.0
10.0
0.0
0.0 10.0 20.0
SECS
W3: AFLDT3.1.Z_FORCE
LBS
100.0
80.0
60.0
40.0
20.0
0.0
0.0 12.0
SECS
W4: AFLDT3.1.HORSEPOW
HP
6.0
4.0
2.0
0.0
0.0 10.0 20.0
SECS
W5: AFLDT3.1.CO2PRES
PSI
10.0
0.0
-10.0
-20.0
-30.0
-40.0
0.0 12.0
SECS
W6: AFLDT3.1.HYDPRES
PSI
50.0
0.0
-50.0
-100.0
0.0 12.0
SECS
W7: AFLDT3.1.CO2WGHT
LBS
156.0
152.0
148.0
0.0 10.0 20.0
SECS
W8: AFLDT3.1.TACH
Volts
4.0
2.0
0.0
0.0 10.0 20.0
SECS
W9: AFLDT3.1.RESULTAN
LBS
80.0
40.0
0.0
0.0 12.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
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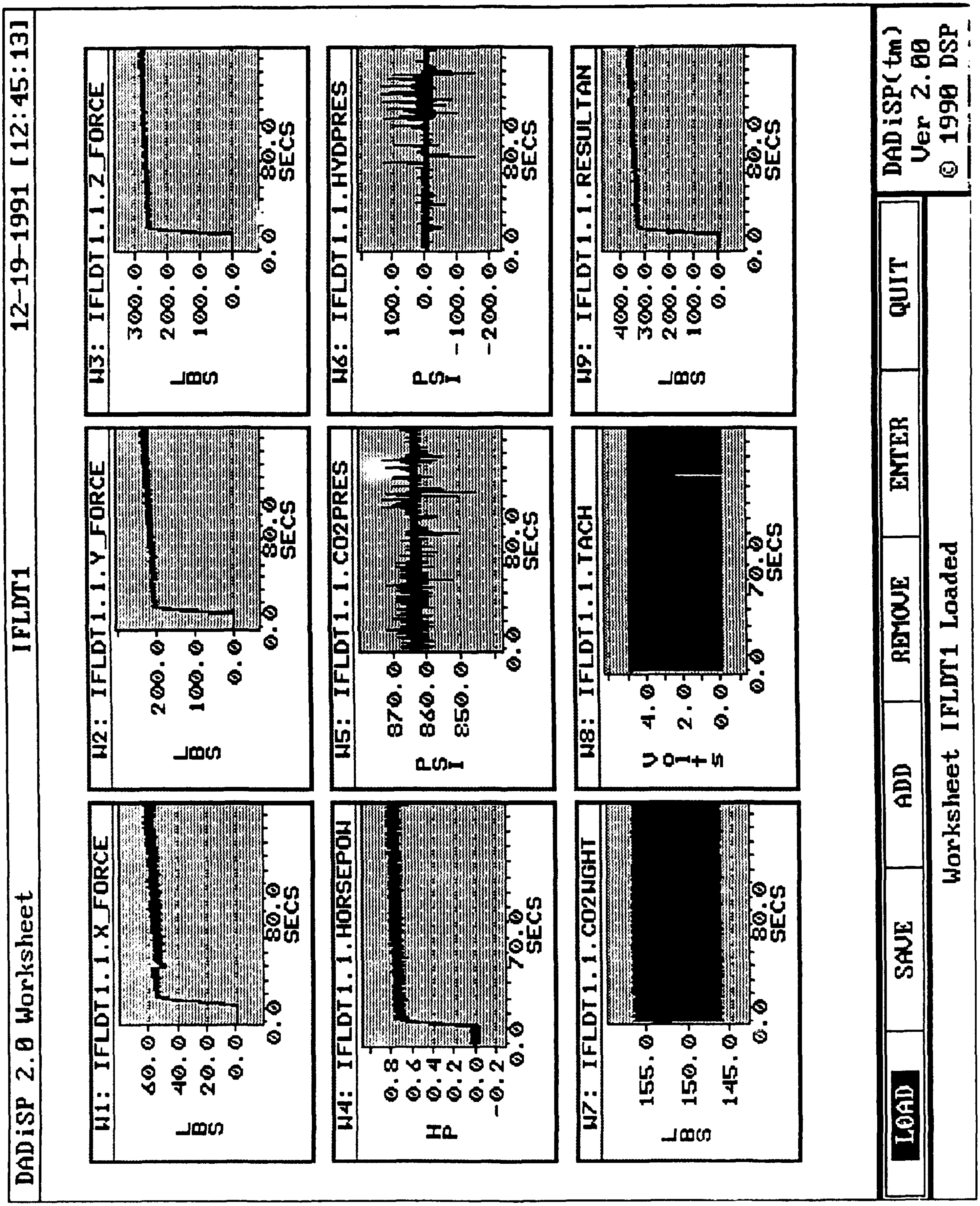
Worksheet AFLDT3 Loaded


DADiSP 2.0 Worksheet
IFLDT1
12-19-1991 [12:45:13]
W1: IFLDT1.1.1.X_FORCE
W2: IFLDT1.1.1.Y_FORCE
W3: IFLDT1.1.1.Z_FORCE
W4: IFLDT1.1.1.HORSEPOW
W5: IFLDT1.1.1.CO2PRES
W6: IFLDT1.1.1.HYDPRES
W7: IFLDT1.1.1.CO2WGHT
W8: IFLDT1.1.1.TACH
W9: IFLDT1.1.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet IFLDT1 Loaded
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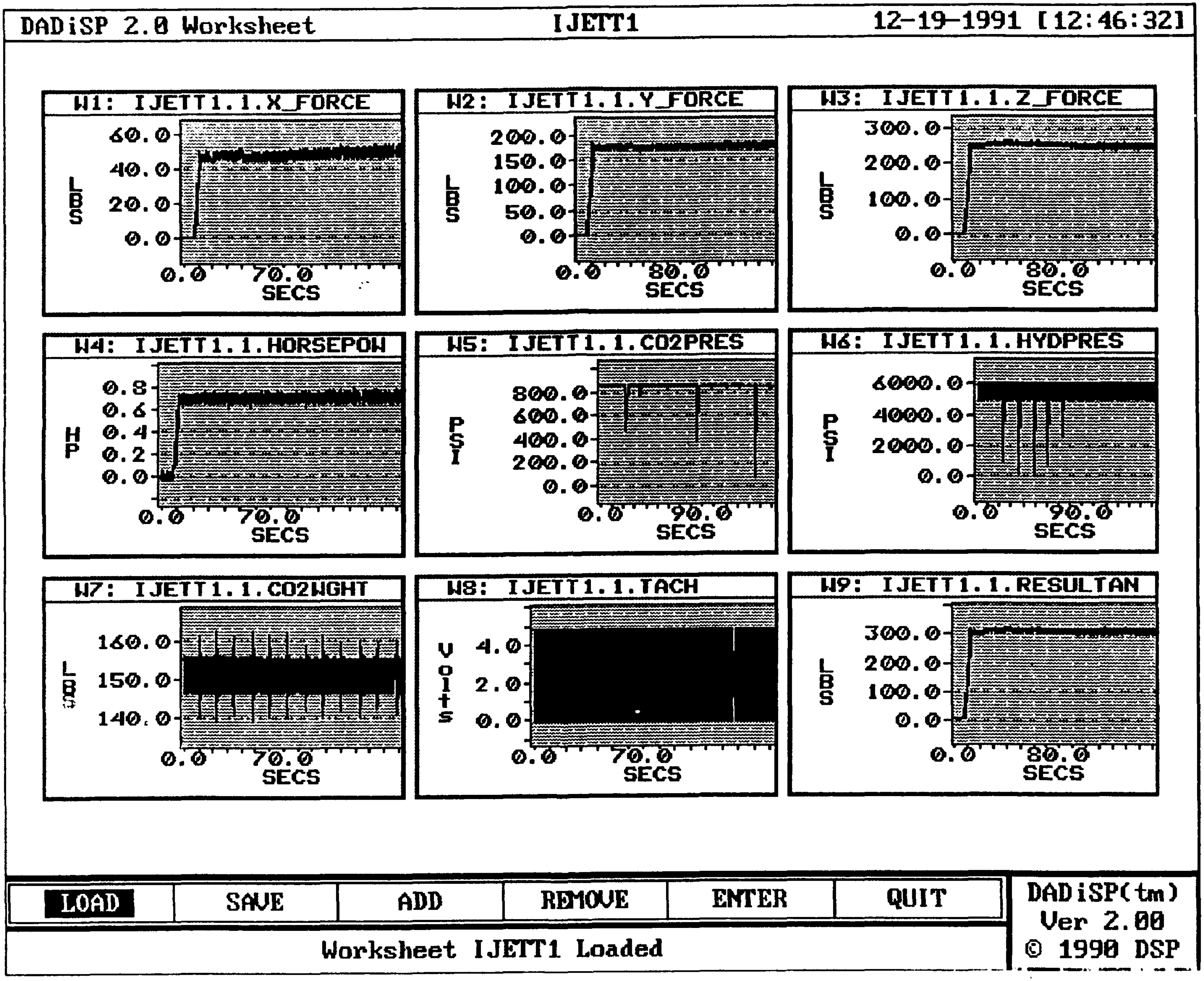
DADiSP 2.0 Worksheet
IJETT1
12-19-1991 [12:46:32]
W1: IJETT1.1.X_FORCE
LBS
60.0
40.0
20.0
0.0
0.0
70.0
SECS
W2: IJETT1.1.Y_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
80.0
SECS
W3: IJETT1.1.Z_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
80.0
SECS
W4: IJETT1.1.HORSEPOW
HP
0.8
0.6
0.4
0.2
0.0
0.0
70.0
SECS
W5: IJETT1.1.CO2PRES
PSI
800.0
600.0
400.0
200.0
0.0
0.0
90.0
SECS
W6: IJETT1.1.HYDPRES
PSI
6000.0
4000.0
2000.0
0.0
0.0
90.0
SECS
W7: IJETT1.1.CO2WGHT
160.0
150.0
140.0
0.0
70.0
SECS
W8: IJETT1.1.TACH
Volts
4.0
2.0
0.0
0.0
70.0
SECS
W9: IJETT1.1.RESULTAN
LBS
300.0
200.0
100.0
0.0
0.0
80.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
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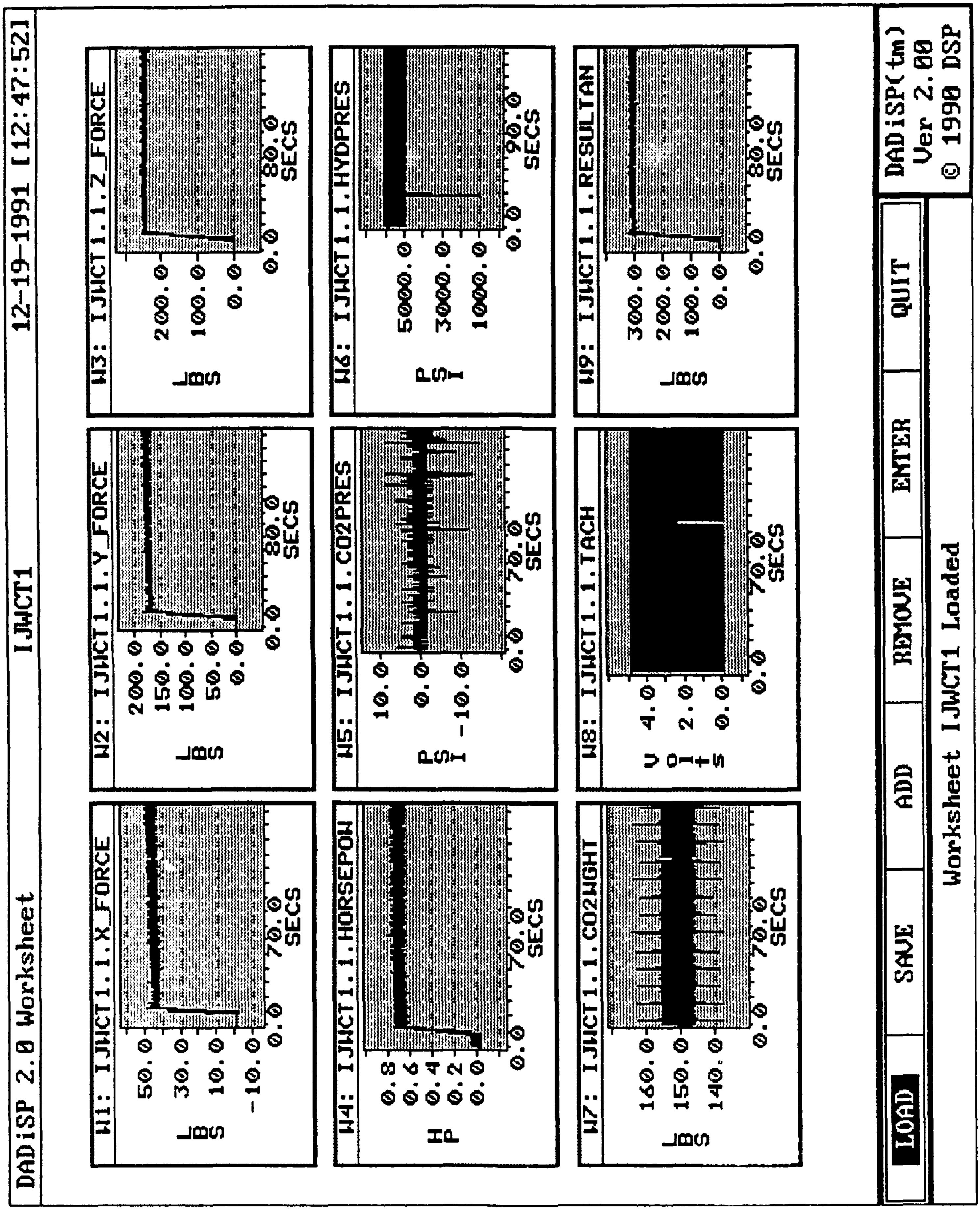
Worksheet IJETT1 Loaded



DADiSP 2.0 Worksheet
IJWCT1
12-19-1991 [12:47:52]
W1: IJWCT1.1.1.X_FORCE
LBS
50.0
30.0
10.0
-10.0
0.0
70.0
SECS
W2: IJWCT1.1.1.Y_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
80.0
SECS
W3: IJWCT1.1.1.Z_FORCE
LBS
200.0
100.0
0.0
0.0
80.0
SECS
W4: IJWCT1.1.HORSEPOW
HP
0.8
0.6
0.4
0.2
0.0
0.0
70.0
SECS
W5: IJWCT1.1.CO2PRES
PSI
10.0
0.0
-10.0
0.0
70.0
SECS
W6: IJWCT1.1.HYDPRES
PSI
5000.0
3000.0
1000.0
0.0
90.0
SECS
W7: IJWCT1.1.CO2WGHT
LBS
160.0
150.0
140.0
0.0
70.0
SECS
W8: IJWCT1.1.TACH
Volts
4.0
2.0
0.0
0.0
70.0
SECS
W9: IJWCT1.1.RESULTAN
LBS
300.0
200.0
100.0
0.0
0.0
80.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
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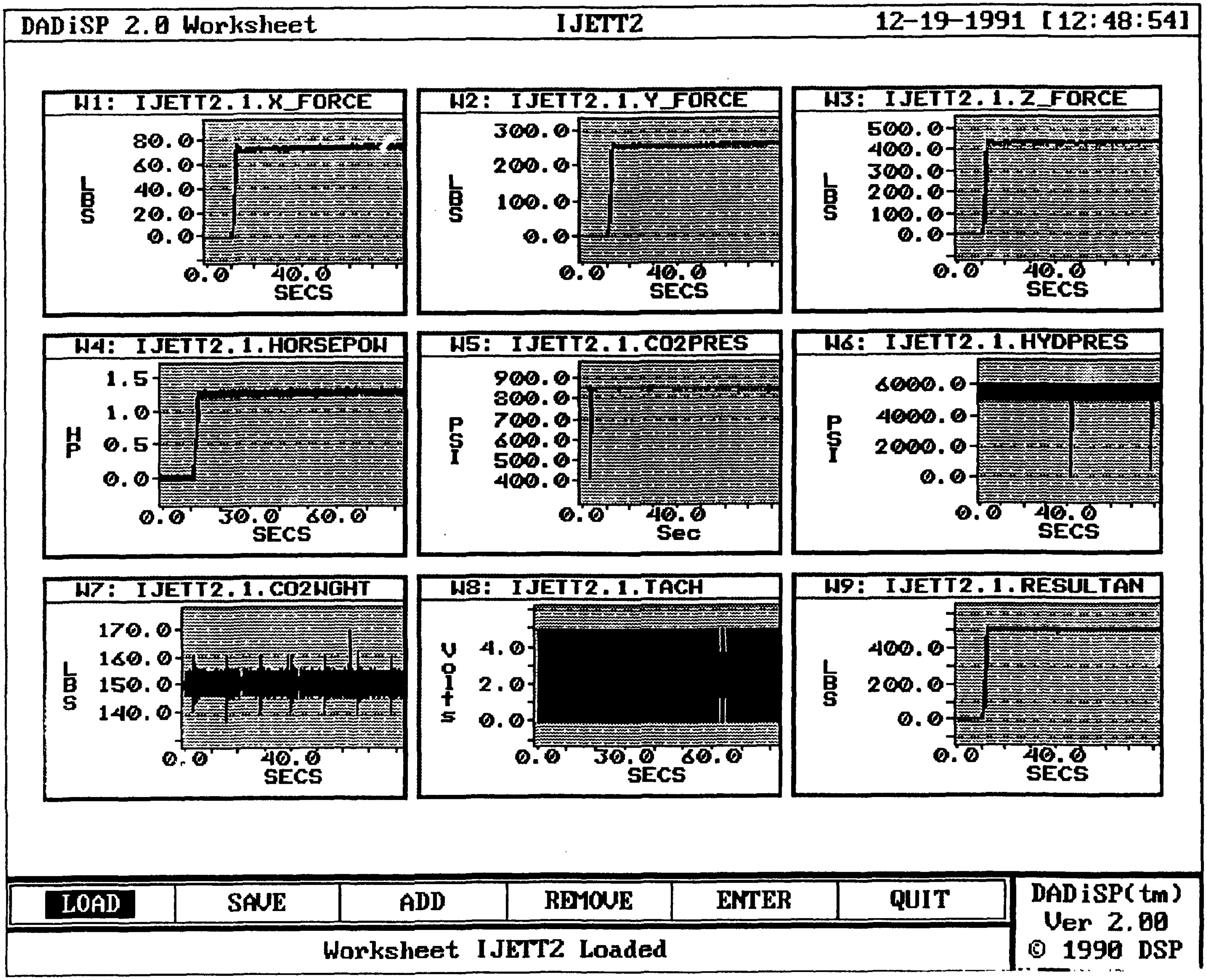
Worksheet IJWCT1 Loaded


DADiSP 2.0 Worksheet
IJETT2
12-19-1991 [12:48:54]
W1: IJETT2.1.X_FORCE
LBS
80.0
60.0
40.0
20.0
0.0
0.0
40.0
SECS
W2: IJETT2.1.Y_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
40.0
SECS
W3: IJETT2.1.Z_FORCE
LBS
500.0
400.0
300.0
200.0
100.0
0.0
0.0
40.0
SECS
W4: IJETT2.1.HORSEPOW
HP
1.5
1.0
0.5
0.0
0.0
30.0
60.0
SECS
W5: IJETT2.1.CO2PRES
PSI
900.0
800.0
700.0
600.0
500.0
400.0
0.0
40.0
Sec
W6: IJETT2.1.HYDPRES
PSI
6000.0
4000.0
2000.0
0.0
0.0
40.0
SECS
W7: IJETT2.1.CO2WGHT
LBS
170.0
160.0
150.0
140.0
0.0
40.0
SECS
W8: IJETT2.1.TACH
Volts
4.0
2.0
0.0
0.0
30.0
60.0
SECS
W9: IJETT2.1.RESULTAN
LBS
400.0
200.0
0.0
0.0
40.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
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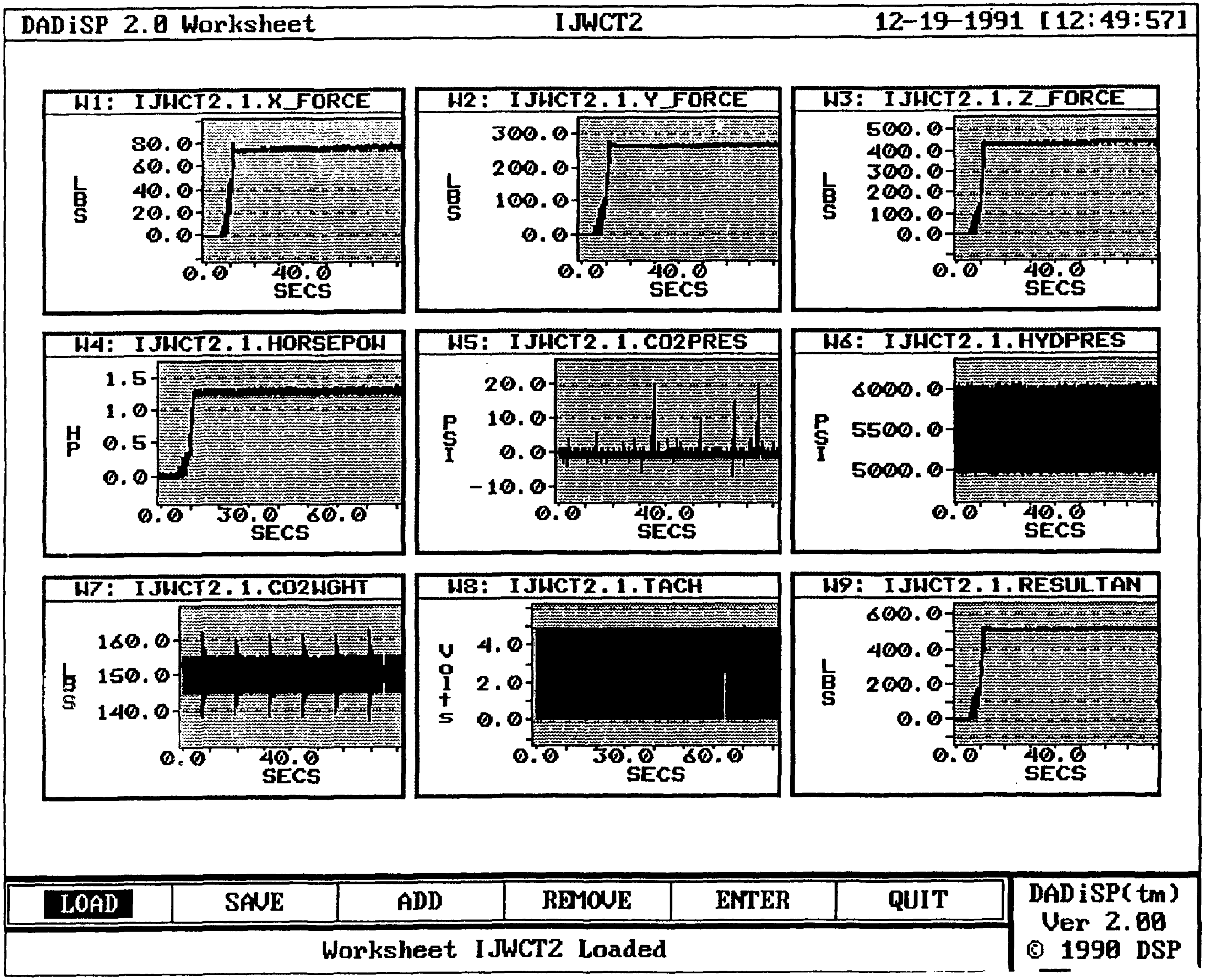
Worksheet IJETT2 Loaded


DADiSP 2.0 Worksheet
IJWCT2
12-19-1991 [12:49:57]
W1: IJWCT2.1.X_FORCE
LBS
80.0
60.0
40.0
20.0
0.0
0.0
40.0
SECS
W2: IJWCT2.1.Y_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
40.0
SECS
W3: IJWCT2.1.Z_FORCE
LBS
500.0
400.0
300.0
200.0
100.0
0.0
0.0
40.0
SECS
W4: IJWCT2.1.HORSEPOW
HP
1.5
1.0
0.5
0.0
0.0
30.0
60.0
SECS
W5: IJWCT2.1.CO2PRES
PSI
20.0
10.0
0.0
-10.0
0.0
40.0
SECS
W6: IJWCT2.1.HYDPRES
PSI
6000.0
5500.0
5000.0
0.0
40.0
SECS
W7: IJWCT2.1.CO2WGHT
LBS
160.0
150.0
140.0
0.0
40.0
SECS
W8: IJWCT2.1.TACH
Volts
4.0
2.0
0.0
0.0
30.0
60.0
SECS
W9: IJWCT2.1.RESULTAN
LBS
600.0
400.0
200.0
0.0
0.0
40.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
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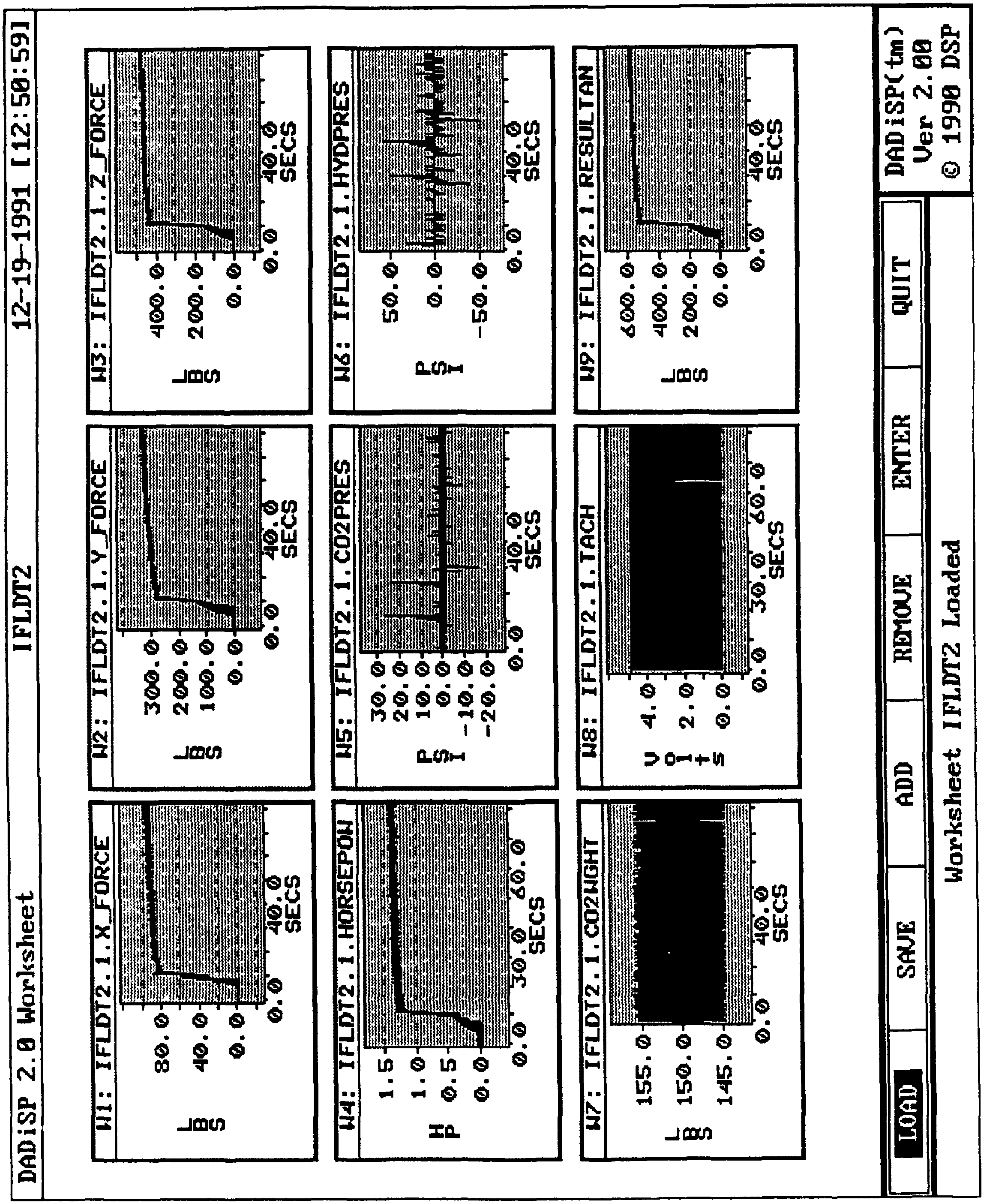
Worksheet IJWCT2 Loaded


DADiSP 2.0 Worksheet
IFLDT2
12-19-1991 [12:50:59]
W1: IFLDT2.1.X_FORCE
W2: IFLDT2.1.Y_FORCE
W3: IFLDT2.1.Z_FORCE
W4: IFLDT2.1.HORSEPOW
W5: IFLDT2.1.CO2PRES
W6: IFLDT2.1.HYDPRES
W7: IFLDT2.1.CO2WGHT
W8: IFLDT2.1.TACH
W9: IFLDT2.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet IFLDT2 Loaded
DADiSP(tm)
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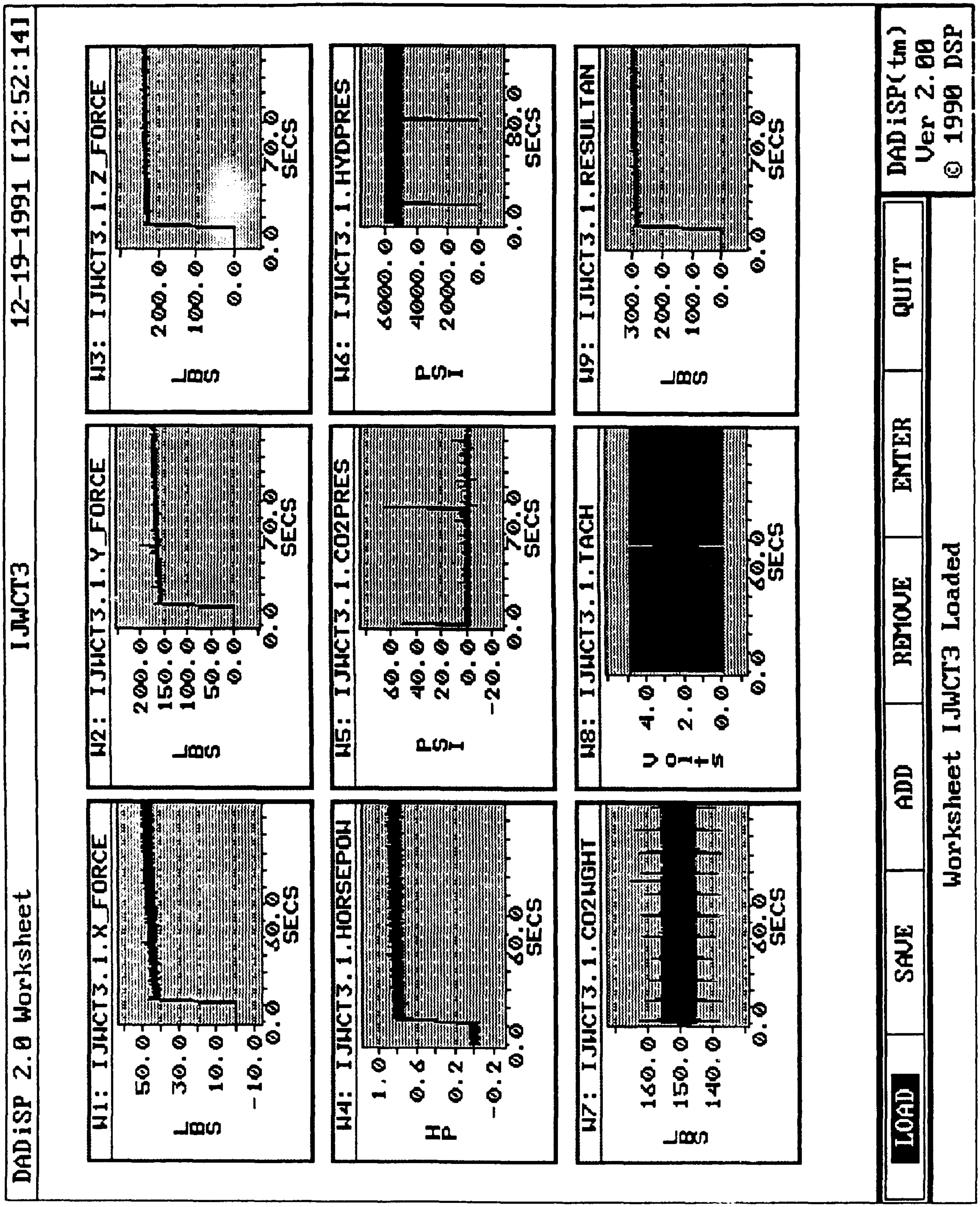

DADiSP 2.0 Worksheet
IJWCT3
12-19-1991 [12:52:14]
W1: IJWCT3.1.X_FORCE
LBS
50.0
30.0
10.0
-10.0
0.0
60.0
SECS
W2: IJWCT3.1.Y_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
70.0
SECS
W3: IJWCT3.1.Z_FORCE
LBS
200.0
100.0
0.0
0.0
70.0
SECS
W4: IJWCT3.1.HORSEPOW
HP
1.0
0.6
0.2
-0.2
0.0
60.0
SECS
W5: IJWCT3.1.CO2PRES
PSI
60.0
40.0
20.0
0.0
-20.0
0.0
70.0
SECS
W6: IJWCT3.1.HYDPRES
PSI
6000.0
4000.0
2000.0
0.0
0.0
80.0
SECS
W7: IJWCT3.1.CO2WGHT
LBS
160.0
150.0
140.0
0.0
60.0
SECS
W8: IJWCT3.1.TACH
Volts
4.0
2.0
0.0
0.0
60.0
SECS
W9: IJWCT3.1.RESULTAN
LBS
300.0
200.0
100.0
0.0
0.0
70.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet IJWCT3 Loaded
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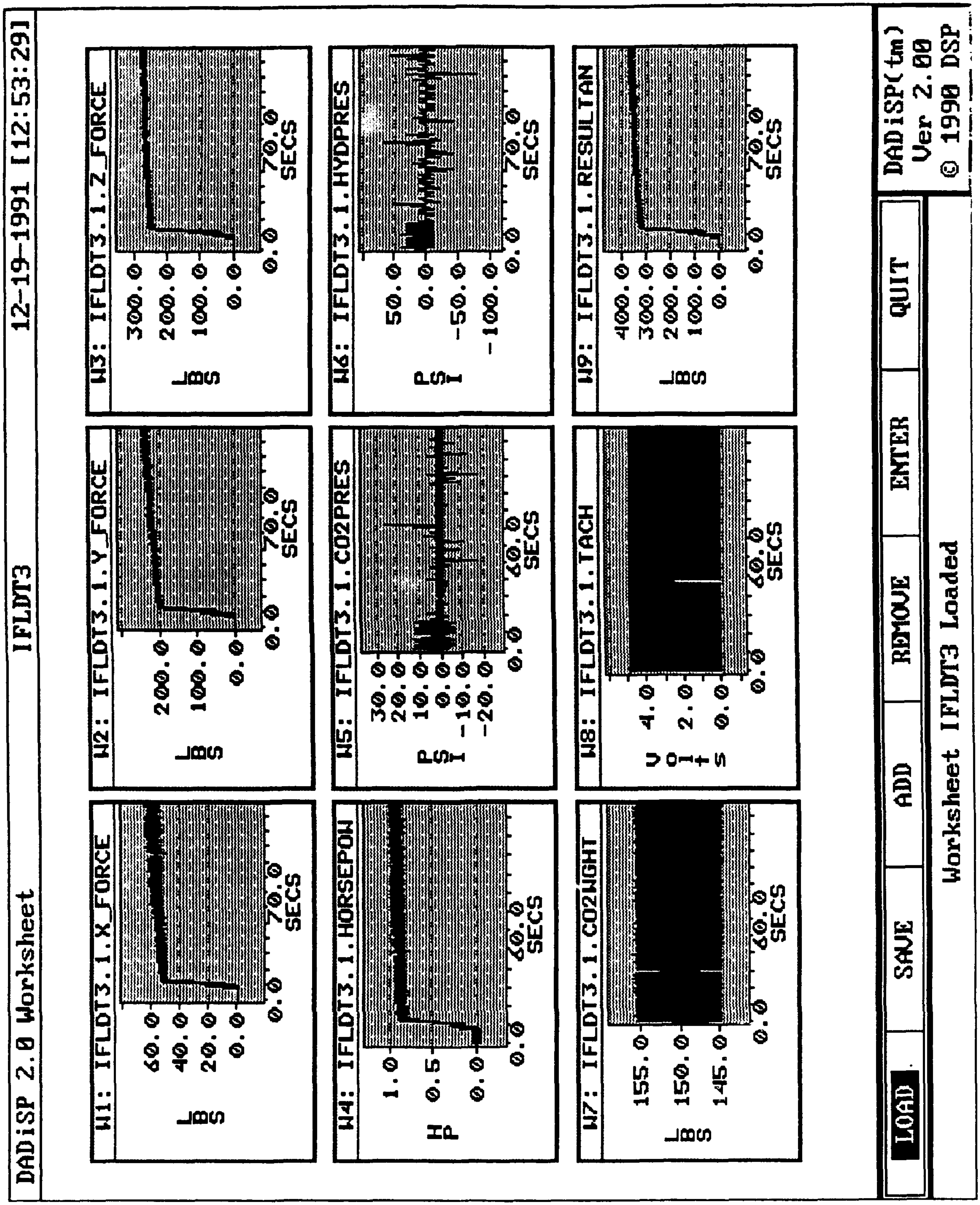
DADiSP 2.0 Worksheet
IFLDT3
12-19-1991 [12:53:29]
W1: IFLDT3.1.X_FORCE
W2: IFLDT3.1.Y_FORCE
W3: IFLDT3.1.Z_FORCE
W4: IFLDT3.1.HORSEPOW
W5: IFLDT3.1.CO2PRES
W6: IFLDT3.1.HYDPRES
W7: IFLDT3.1.CO2WGHT
W8: IFLDT3.1.TACH
W9: IFLDT3.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet IFLDT3 Loaded
DADiSP(tm)
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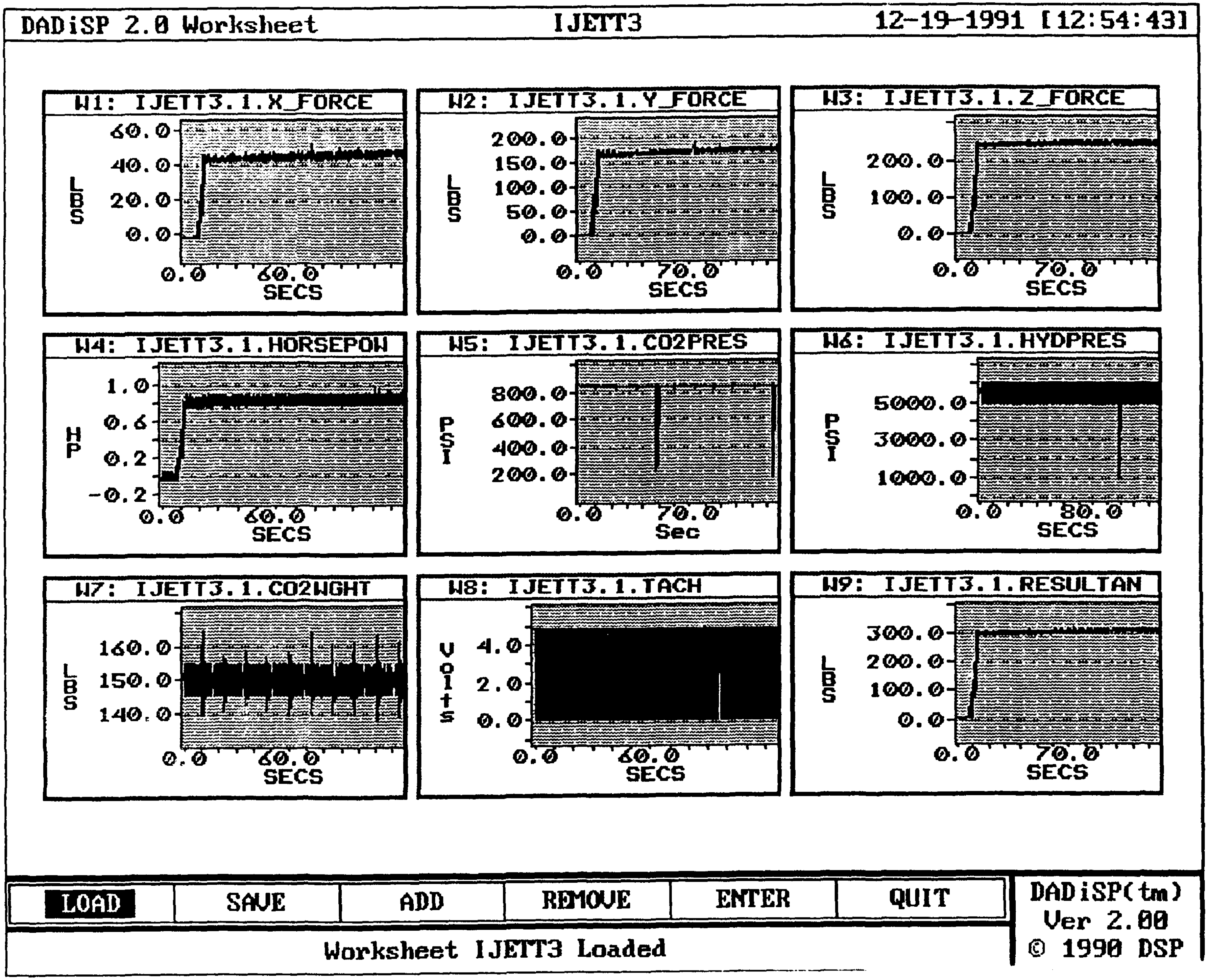

DADiSP 2.0 Worksheet
IJETT3
12-19-1991 [12:54:43]
W1: IJETT3.1.X_FORCE
LBS
60.0
40.0
20.0
0.0
0.0
60.0
SECS
W2: IJETT3.1.Y_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
70.0
SECS
W3: IJETT3.1.Z_FORCE
LBS
200.0
100.0
0.0
0.0
70.0
SECS
W4: IJETT3.1.HORSEPOW
HP
1.0
0.6
0.2
-0.2
0.0
60.0
SECS
W5: IJETT3.1.CO2PRES
PSI
800.0
600.0
400.0
200.0
0.0
70.0
Sec
W6: IJETT3.1.HYDPRES
PSI
5000.0
3000.0
1000.0
0.0
80.0
SECS
W7: IJETT3.1.CO2WGHT
LBS
160.0
150.0
140.0
0.0
60.0
SECS
W8: IJETT3.1.TACH
Volts
4.0
2.0
0.0
0.0
60.0
SECS
W9: IJETT3.1.RESULTAN
LBS
300.0
200.0
100.0
0.0
0.0
70.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
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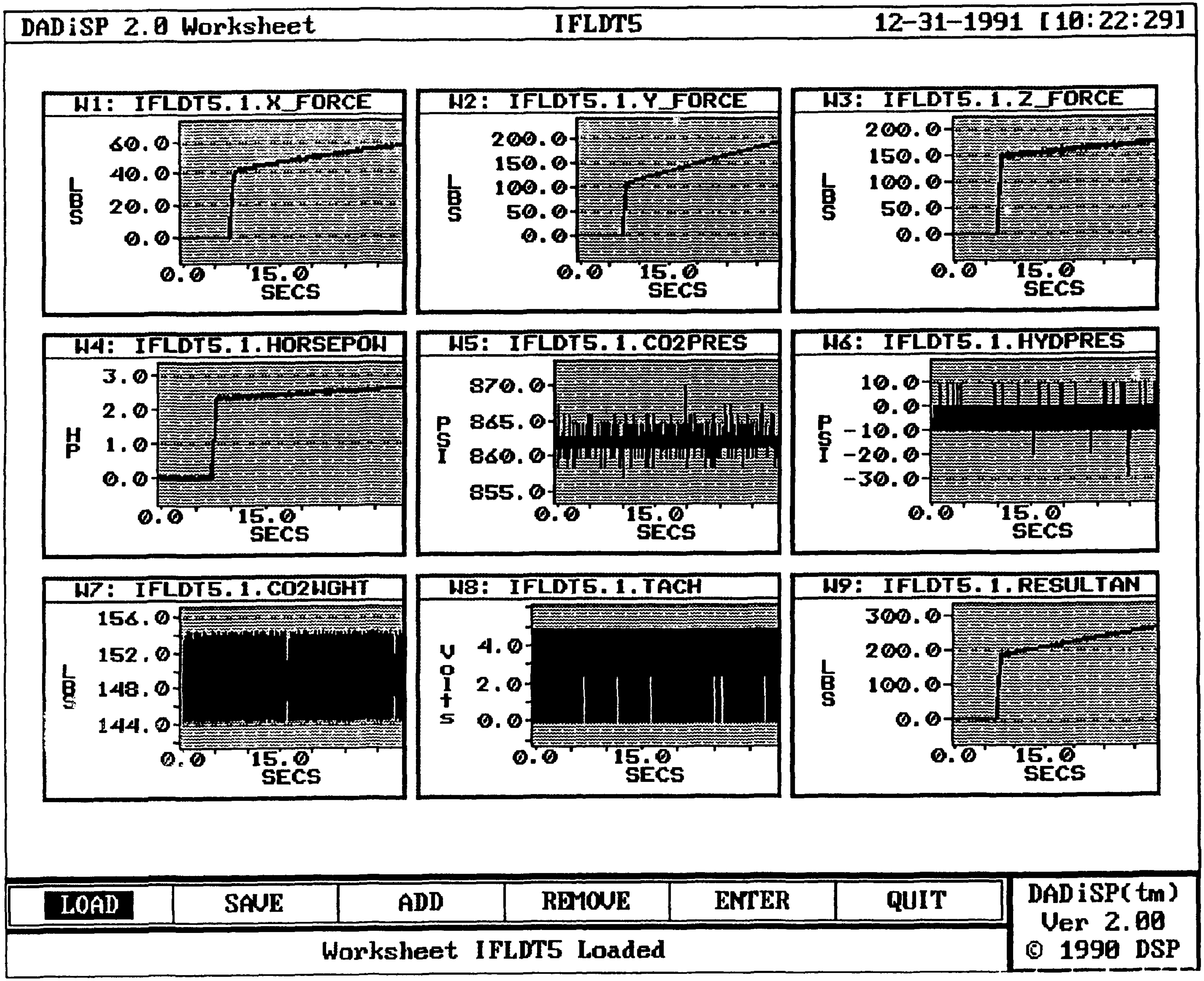
Worksheet IJETT3 Loaded



DADiSP 2.0 Worksheet
IFLDT5
12-31-1991 [10:22:29]
W1: IFLDT5.1.X_FORCE
LBS
60.0
40.0
20.0
0.0
0.0
15.0
SECS
W2: IFLDT5.1.Y_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
15.0
SECS
W3: IFLDT5.1.Z_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
15.0
SECS
W4: IFLDT5.1.HORSEPOW
HP
3.0
2.0
1.0
0.0
0.0
15.0
SECS
W5: IFLDT5.1.CO2PRES
PSI
870.0
865.0
860.0
855.0
0.0
15.0
SECS
W6: IFLDT5.1.HYDPRES
PSI
10.0
0.0
-10.0
-20.0
-30.0
0.0
15.0
SECS
W7: IFLDT5.1.CO2WGHT
LBS
156.0
152.0
148.0
144.0
0.0
15.0
SECS
W8: IFLDT5.1.TACH
Volts
4.0
2.0
0.0
0.0
15.0
SECS
W9: IFLDT5.1.RESULTAN
LBS
300.0
200.0
100.0
0.0
0.0
15.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
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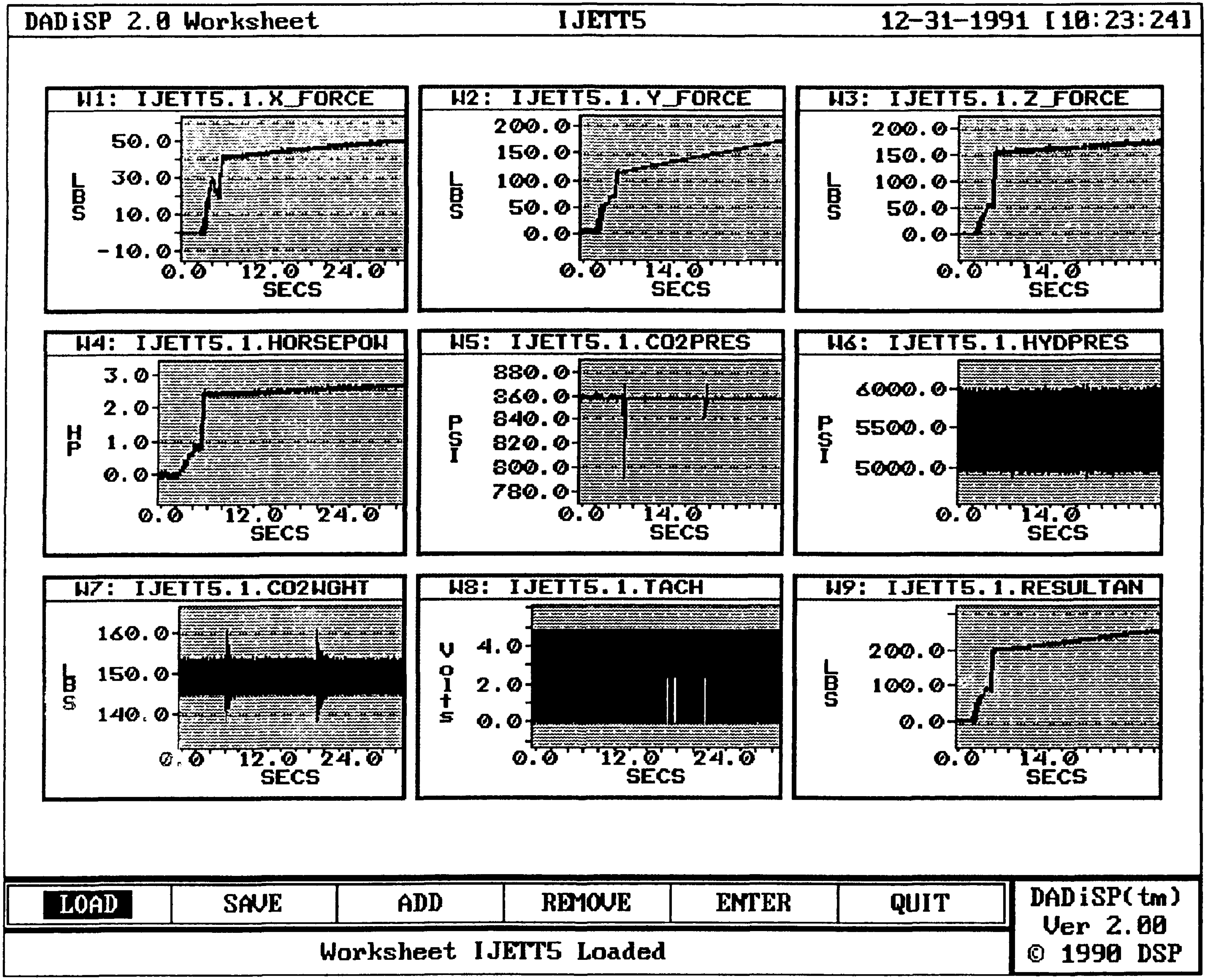
Worksheet IFLDT5 Loaded


DADiSP 2.0 Worksheet
IJETT5
12-31-1991 [10:23:24]
W1: IJETT5.1.X_FORCE
LBS
50.0
30.0
10.0
-10.0
0.0
12.0
24.0
SECS
W2: IJETT5.1.Y_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
14.0
SECS
W3: IJETT5.1.Z_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
14.0
SECS
W4: IJETT5.1.HORSEPOW
HP
3.0
2.0
1.0
0.0
0.0
12.0
24.0
SECS
W5: IJETT5.1.CO2PRES
PSI
880.0
860.0
840.0
820.0
800.0
780.0
0.0
14.0
SECS
W6: IJETT5.1.HYDPRES
PSI
6000.0
5500.0
5000.0
0.0
14.0
SECS
W7: IJETT5.1.CO2WGHT
LBS
160.0
150.0
140.0
0.0
12.0
24.0
SECS
W8: IJETT5.1.TACH
Volts
4.0
2.0
0.0
0.0
12.0
24.0
SECS
W9: IJETT5.1.RESULTAN
LBS
200.0
100.0
0.0
0.0
14.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
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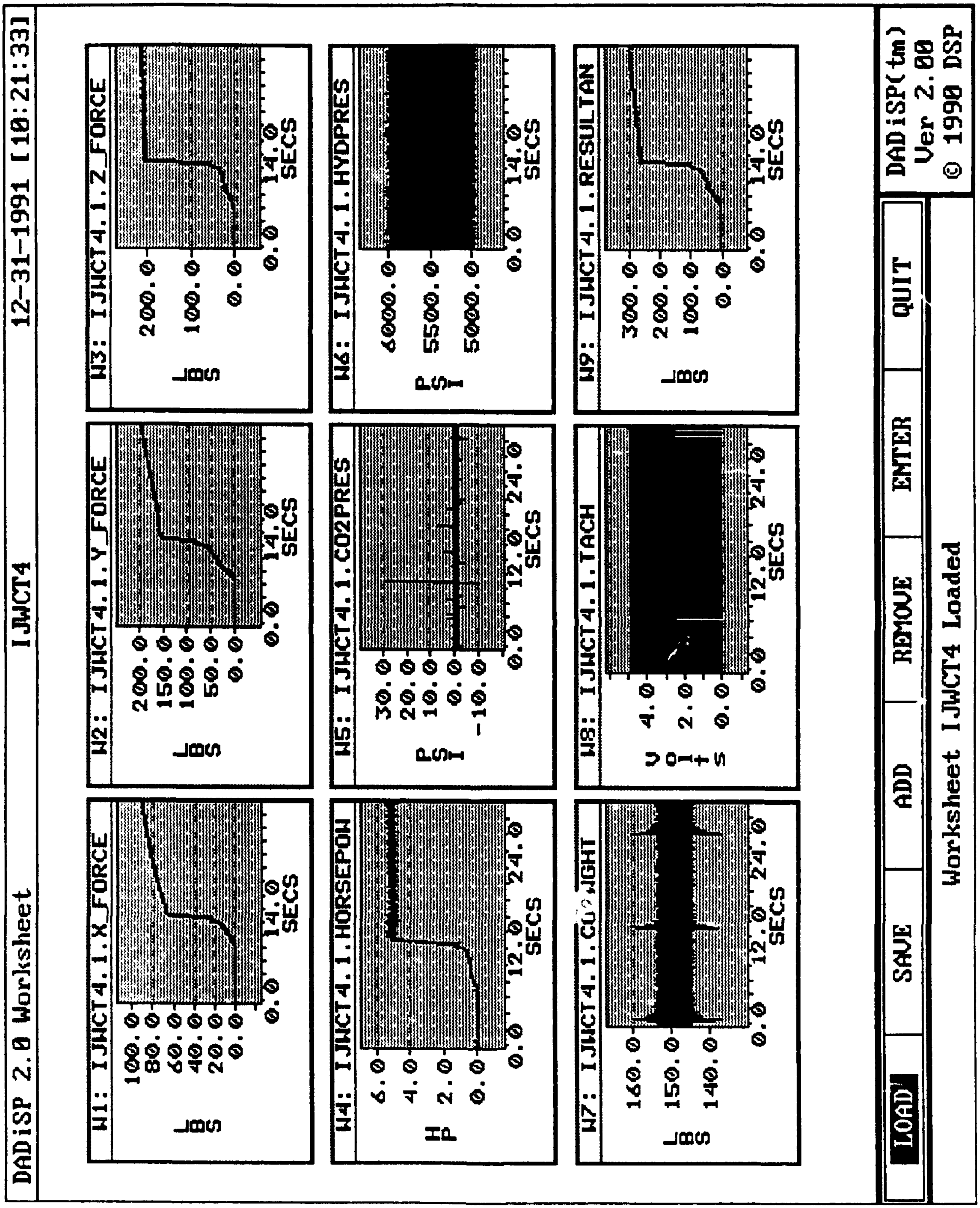
Worksheet IJETT5 Loaded



DADiSP 2.0 Worksheet
IJWCT4
12-31-1991 [10:21:33]
W1: IJWCT4.1.X_FORCE
W2: IJWCT4.1.Y_FORCE
W3: IJWCT4.1.Z_FORCE
W4: IJWCT4.1.HORSEPOW
W5: IJWCT4.1.CO2PRES
W6: IJWCT4.1.HYDPRES
W7: IJWCT4.1.CO2WGHT
W8: IJWCT4.1.TACH
W9: IJWCT4.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet IJWCT4 Loaded
DADiSP(tm)
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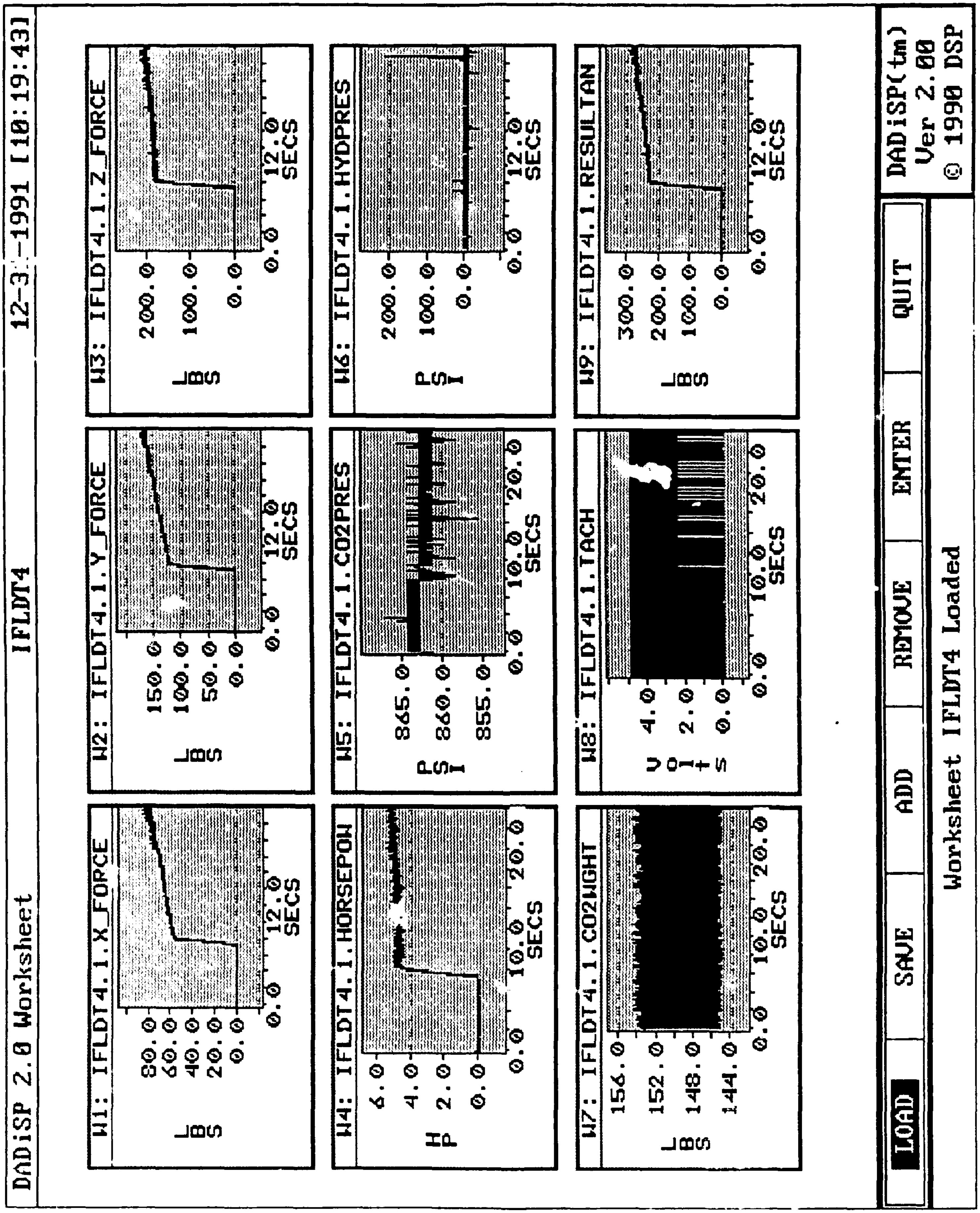
DADiSP 2.0 Worksheet
IFLDT4
W1: IFLDT4.1.X_FORCE
W2: IFLDT4.1.Y_FORCE
W3: IFLDT4.1.Z_FORCE
W4: IFLDT4.1.HORSEPOW
W5: IFLDT4.1.CO2PRES
W6: IFLDT4.1.HYDPRES
W7: IFLDT4.1.CO2WGHT
W8: IFLDT4.1.TACH
W9: IFLDT4.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet IFLDT4 Loaded
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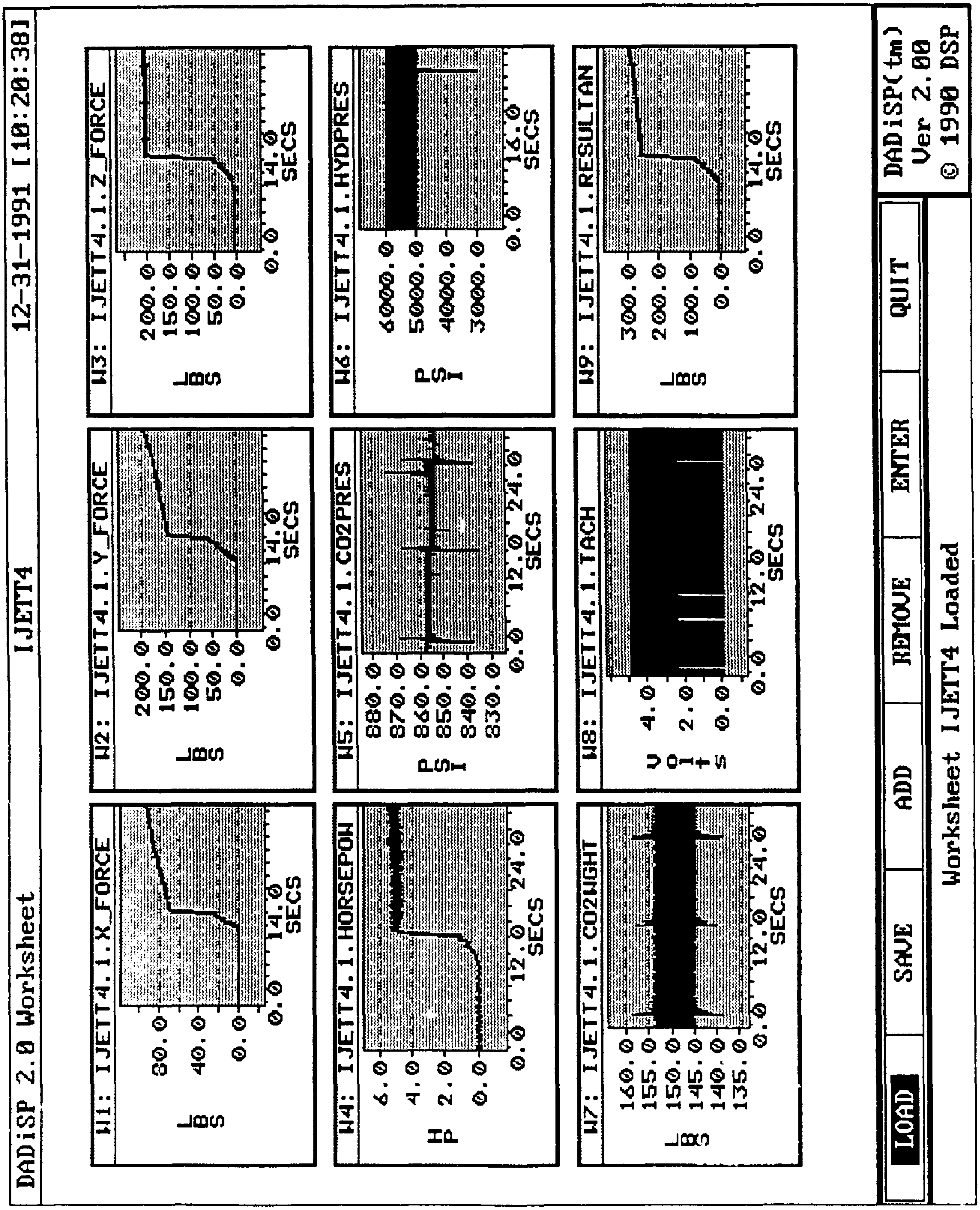

DADiSP 2.0 Worksheet
IJETT4
12-31-1991 [10:20:38]
W1: IJETT4.1.X_FORCE
LBS
80.0
40.0
0.0
0.0
14.0
SECS
W2: IJETT4.1.Y_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
14.0
SECS
W3: IJETT4.1.Z_FORCE
LBS
200.0
150.0
100.0
50.0
0.0
0.0
14.0
SECS
W4: IJETT4.1.HORSEPOW
HP
6.0
4.0
2.0
0.0
0.0
12.0
24.0
SECS
W5: IJETT4.1.CO2PRES
PSI
880.0
870.0
860.0
850.0
840.0
830.0
0.0
12.0
24.0
SECS
W6: IJETT4.1.HYDPRES
PSI
6000.0
5000.0
4000.0
3000.0
0.0
14.0
SECS
W7: IJETT4.1.CO2WGHT
LBS
160.0
155.0
150.0
145.0
140.0
135.0
0.0
12.0
24.0
SECS
W8: IJETT4.1.TACH
Volts
4.0
2.0
0.0
0.0
12.0
24.0
SECS
W9: IJETT4.1.RESULTAN
LBS
300.0
200.0
100.0
0.0
0.0
14.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
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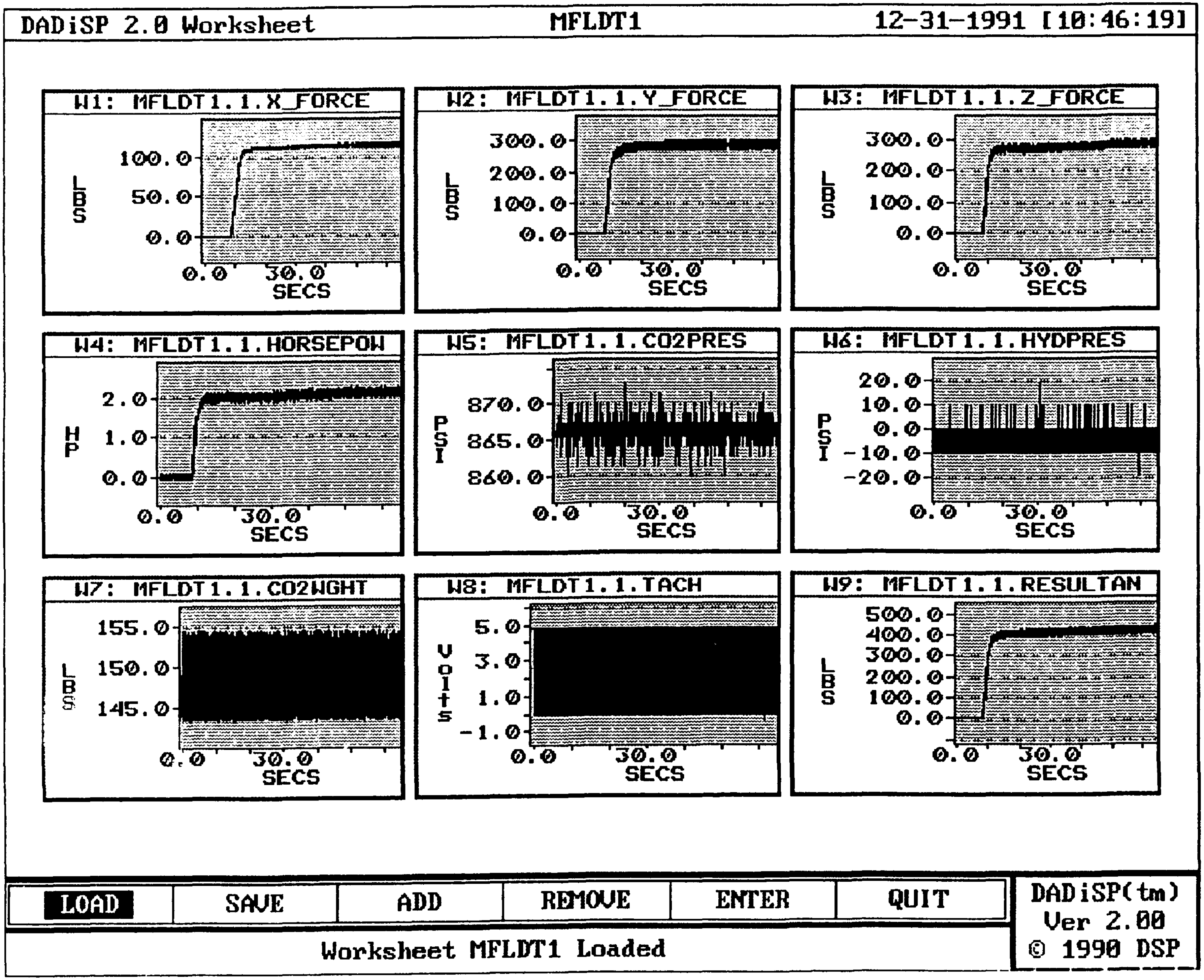
Worksheet IJETT4 Loaded



DADiSP 2.0 Worksheet
MFLDT1
12-31-1991 [10:46:19]
W1: MFLDT1.1.X_FORCE
W2: MFLDT1.1.Y_FORCE
W3: MFLDT1.1.Z_FORCE
W4: MFLDT1.1.HORSEPOW
W5: MFLDT1.1.CO2PRES
W6: MFLDT1.1.HYDPRES
W7: MFLDT1.1.CO2WGHT
W8: MFLDT1.1.TACH
W9: MFLDT1.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet MFLDT1 Loaded
DADiSP(tm)
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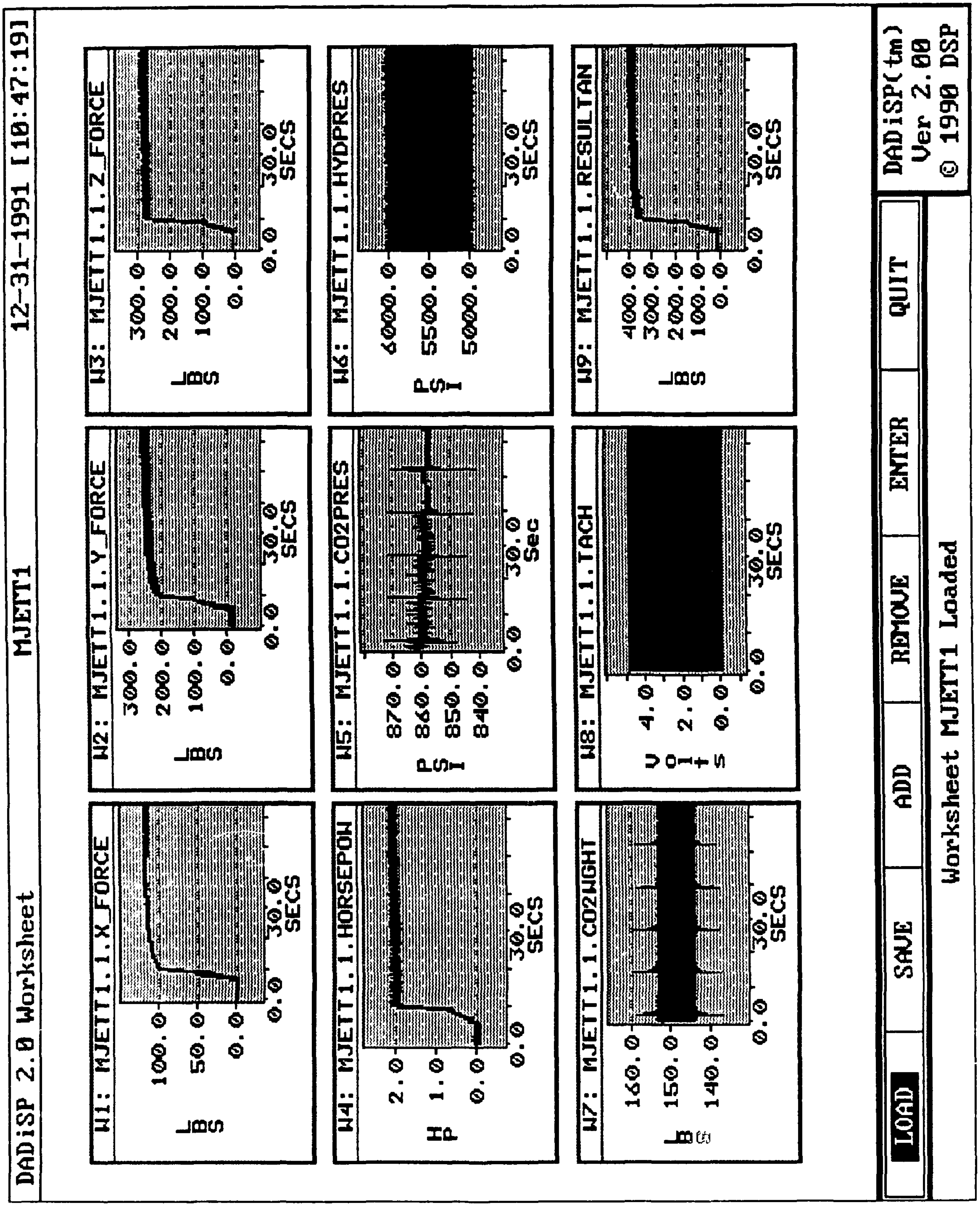
DADiSP 2.0 Worksheet
MJETT1
12-31-1991 [10:47:19]
W1: MJETT1.1.X_FORCE
W2: MJETT1.1.Y_FORCE
W3: MJETT1.1.Z_FORCE
W4: MJETT1.1.HORSEPOW
W5: MJETT1.1.CO2PRES
W6: MJETT1.1.HYDPRES
W7: MJETT1.1.CO2WGHT
W8: MJETT1.1.TACH
W9: MJETT1.1.RESULTAN
LBS
HP
PSI
Volts
SECS
Sec
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet MJETT1 Loaded
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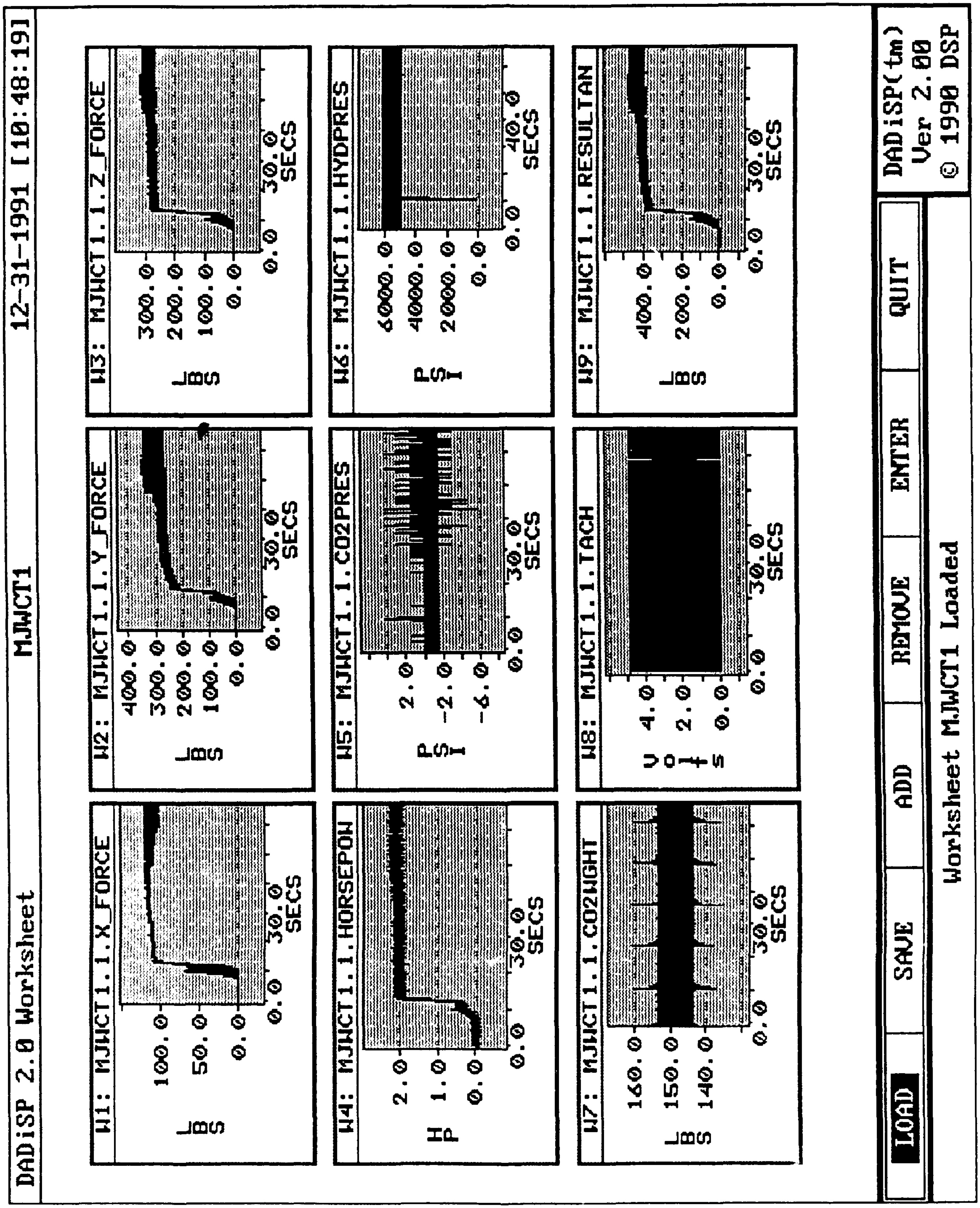

DADiSP 2.0 Worksheet
MJWCT1
12-31-1991 [10:48:19]
W1: MJWCT1.1.1.X_FORCE
W2: MJWCT1.1.1.Y_FORCE
W3: MJWCT1.1.1.Z_FORCE
W4: MJWCT1.1.1.HORSEPOW
W5: MJWCT1.1.1.CO2PRES
W6: MJWCT1.1.1.HYDPRES
W7: MJWCT1.1.1.CO2WGHT
W8: MJWCT1.1.1.TACH
W9: MJWCT1.1.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet MJWCT1 Loaded
DADiSP(tm)
Ver 2.00
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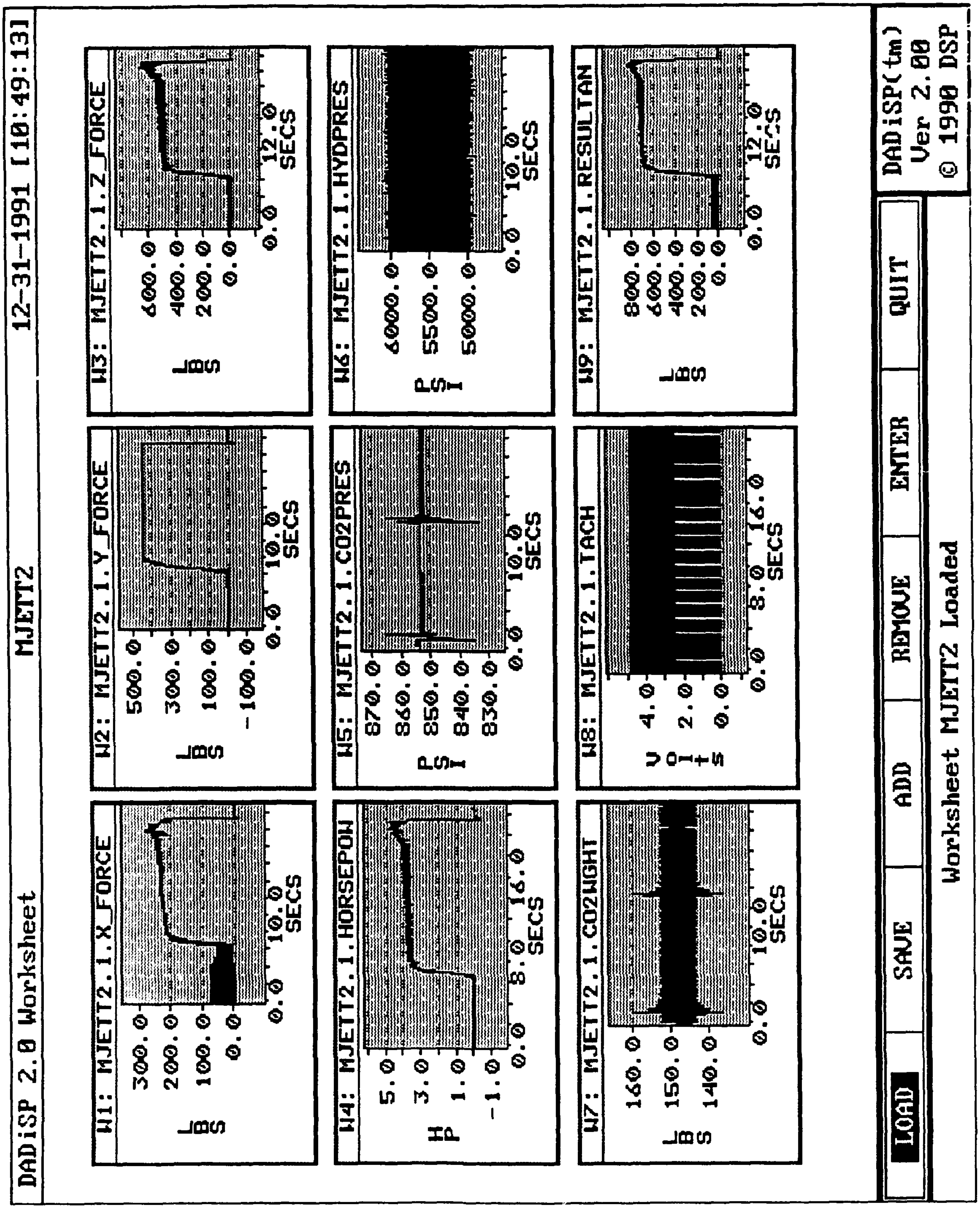
DADiSP 2.0 Worksheet
MJETT2
12-31-1991 [10:49:13]
W1: MJETT2.1.X_FORCE
W2: MJETT2.1.Y_FORCE
W3: MJETT2.1.Z_FORCE
W4: MJETT2.1.HORSEPOW
W5: MJETT2.1.CO2PRES
W6: MJETT2.1.HYDPRES
W7: MJETT2.1.CO2WGHT
W8: MJETT2.1.TACH
W9: MJETT2.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet MJETT2 Loaded
DADiSP(tm)
Ver 2.00
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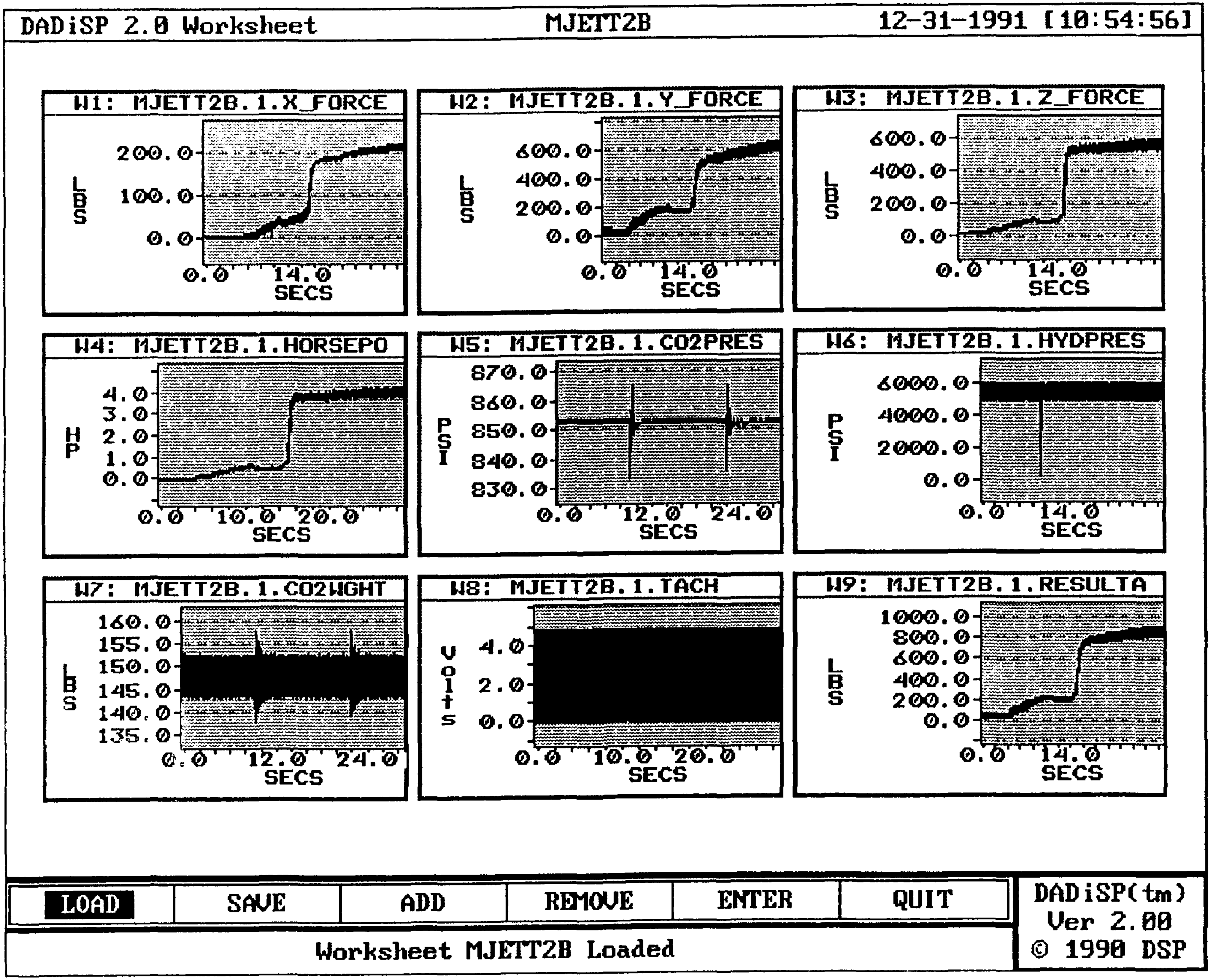
DADiSP 2.0 Worksheet
MJETT2B
12-31-1991 [10:54:56]
W1: MJETT2B.1.X_FORCE
LBS
200.0
100.0
0.0
0.0
14.0
SECS
W2: MJETT2B.1.Y_FORCE
LBS
600.0
400.0
200.0
0.0
0.0
14.0
SECS
W3: MJETT2B.1.Z_FORCE
LBS
600.0
400.0
200.0
0.0
0.0
14.0
SECS
W4: MJETT2B.1.HORSEPO
HP
4.0
3.0
2.0
1.0
0.0
0.0
10.0
20.0
SECS
W5: MJETT2B.1.CO2PRES
PSI
870.0
860.0
850.0
840.0
830.0
0.0
12.0
24.0
SECS
W6: MJETT2B.1.HYDPRES
PSI
6000.0
4000.0
2000.0
0.0
0.0
14.0
SECS
W7: MJETT2B.1.CO2WGHT
LBS
160.0
155.0
150.0
145.0
140.0
135.0
0.0
12.0
24.0
SECS
W8: MJETT2B.1.TACH
Volts
4.0
2.0
0.0
0.0
10.0
20.0
SECS
W9: MJETT2B.1.RESULTA
LBS
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
14.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
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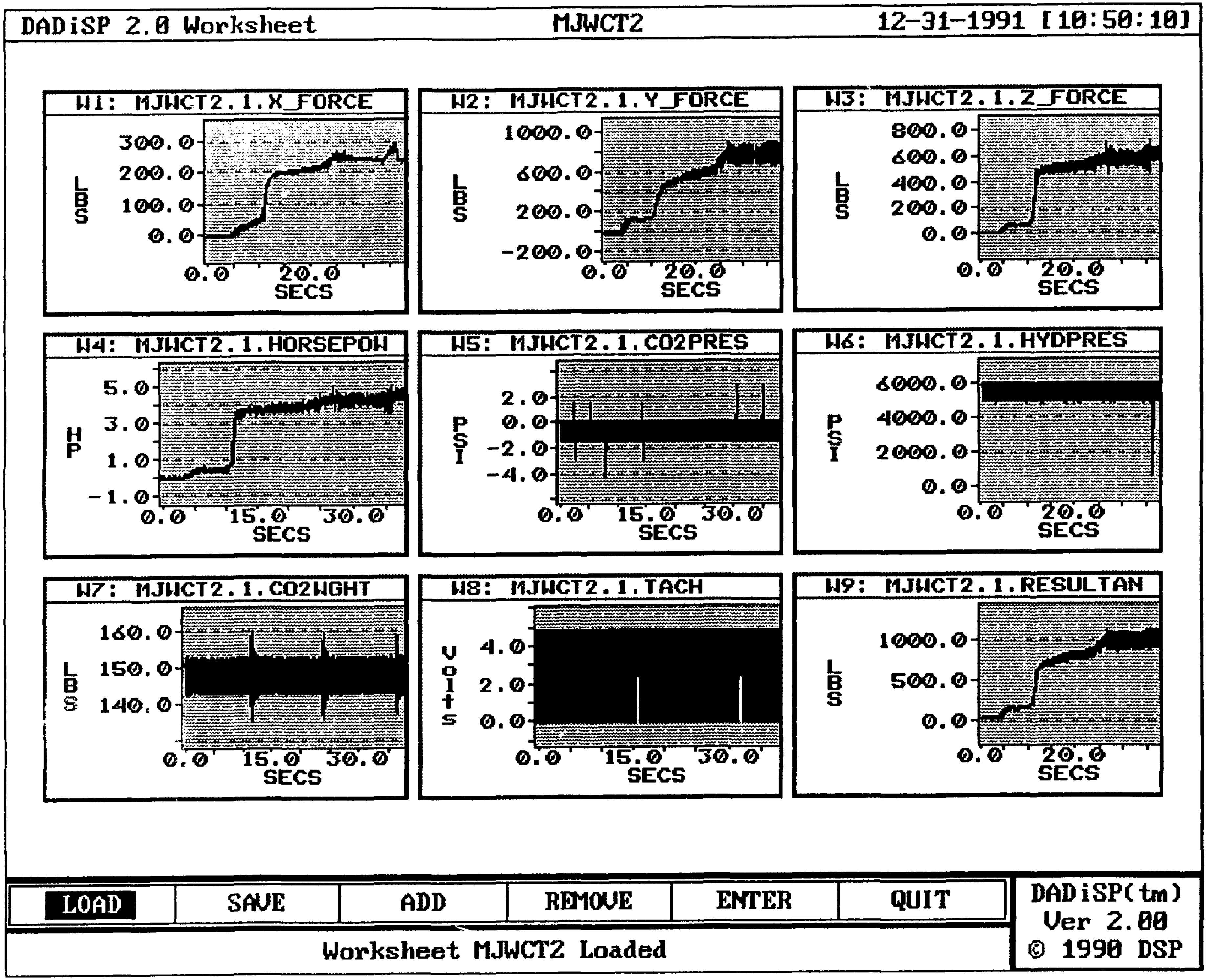
Worksheet MJETT2B Loaded



DADiSP 2.0 Worksheet
MJWCT2
12-31-1991 [10:50:10]
W1: MJWCT2.1.X_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
20.0
SECS
W2: MJWCT2.1.Y_FORCE
LBS
1000.0
600.0
200.0
-200.0
0.0
20.0
SECS
W3: MJWCT2.1.Z_FORCE
LBS
800.0
600.0
400.0
200.0
0.0
0.0
20.0
SECS
W4: MJWCT2.1.HORSEPOW
HP
5.0
3.0
1.0
-1.0
0.0
15.0
30.0
SECS
W5: MJWCT2.1.CO2PRES
PSI
2.0
0.0
-2.0
-4.0
0.0
15.0
30.0
SECS
W6: MJWCT2.1.HYDPRES
PSI
6000.0
4000.0
2000.0
0.0
0.0
20.0
SECS
W7: MJWCT2.1.CO2WGHT
LBS
160.0
150.0
140.0
0.0
15.0
30.0
SECS
W8: MJWCT2.1.TACH
Volts
4.0
2.0
0.0
0.0
15.0
30.0
SECS
W9: MJWCT2.1.RESULTAN
LBS
1000.0
500.0
0.0
0.0
20.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
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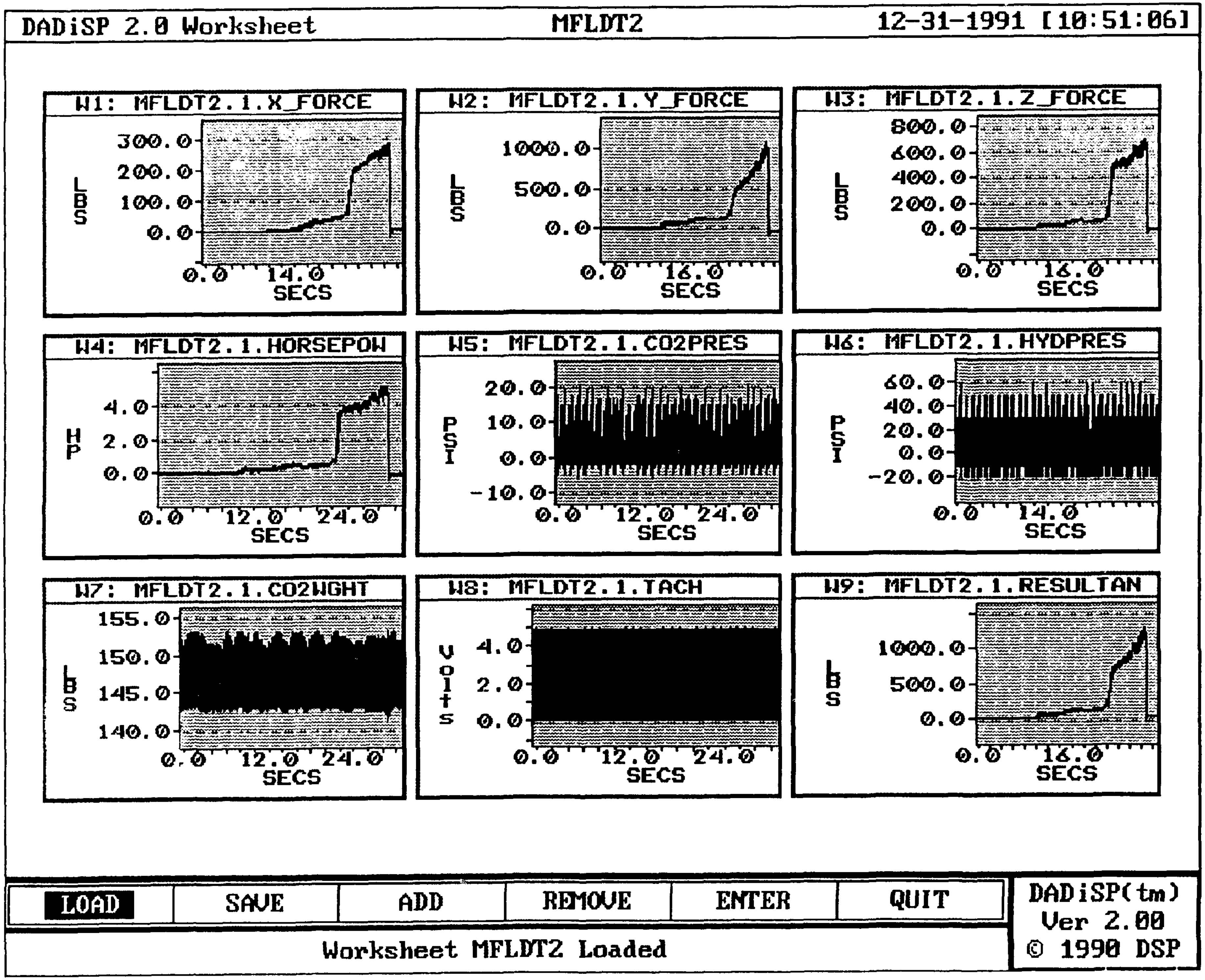
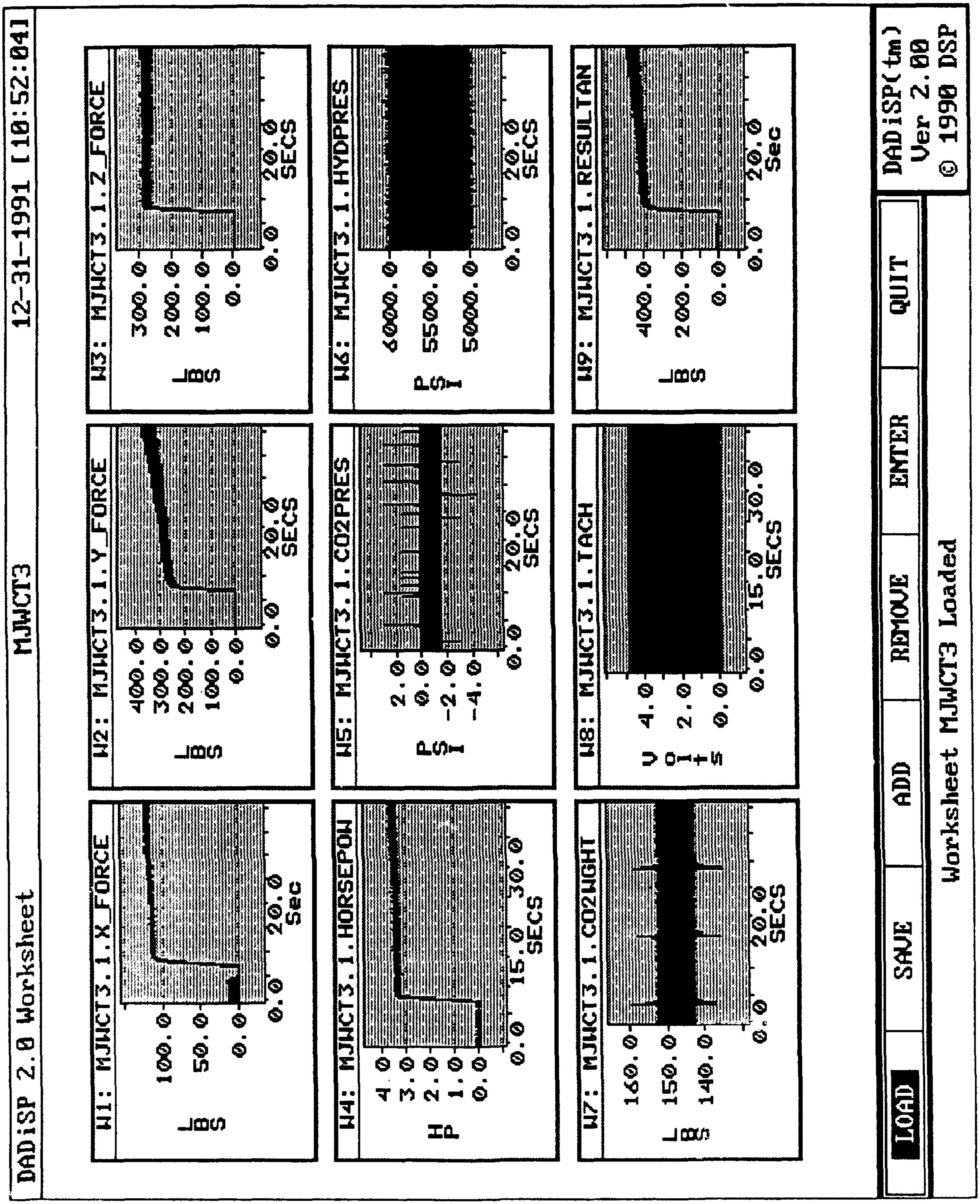
Worksheet MJWCT2 Loaded


DADiSP 2.0 Worksheet
MFLDT2
12-31-1991 [10:51:06]
W1: MFLDT2.1.X_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
14.0
SECS
W2: MFLDT2.1.Y_FORCE
LBS
1000.0
500.0
0.0
0.0
16.0
SECS
W3: MFLDT2.1.Z_FORCE
LBS
800.0
600.0
400.0
200.0
0.0
0.0
16.0
SECS
W4: MFLDT2.1.HORSEPOW
HP
4.0
2.0
0.0
0.0
12.0
24.0
SECS
W5: MFLDT2.1.CO2PRES
PSI
20.0
10.0
0.0
-10.0
0.0
12.0
24.0
SECS
W6: MFLDT2.1.HYDPRES
PSI
60.0
40.0
20.0
0.0
-20.0
0.0
14.0
SECS
W7: MFLDT2.1.CO2WGHT
LBS
155.0
150.0
145.0
140.0
0.0
12.0
24.0
SECS
W8: MFLDT2.1.TACH
Volts
4.0
2.0
0.0
0.0
12.0
24.0
SECS
W9: MFLDT2.1.RESULTAN
LBS
1000.0
500.0
0.0
0.0
16.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
DADiSP(tm)
Ver 2.00
© 1990 DSP
Worksheet MFLDT2 Loaded


DADiSP 2.0 Worksheet
MJWCT3
12-31-1991 [10:52:04]
W1: MJWCT3.1.X_FORCE
LBS
100.0
50.0
0.0
0.0
20.0
Sec
W2: MJWCT3.1.Y_FORCE
LBS
400.0
300.0
200.0
100.0
0.0
0.0
20.0
SECS
W3: MJWCT3.1.Z_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
20.0
SECS
W4: MJWCT3.1.HORSEPOW
HP
4.0
3.0
2.0
1.0
0.0
0.0
15.0
30.0
SECS
W5: MJWCT3.1.CO2PRES
PSI
2.0
0.0
-2.0
-4.0
0.0
20.0
SECS
W6: MJWCT3.1.HYDPRES
PSI
6000.0
5500.0
5000.0
0.0
20.0
SECS
W7: MJWCT3.1.CO2WGHT
LBS
160.0
150.0
140.0
0.0
20.0
SECS
W8: MJWCT3.1.TACH
Volts
4.0
2.0
0.0
0.0
15.0
30.0
SECS
W9: MJWCT3.1.RESULTAN
LBS
400.0
200.0
0.0
0.0
20.0
Sec
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet MJWCT3 Loaded
DADiSP(tm)
Ver 2.00
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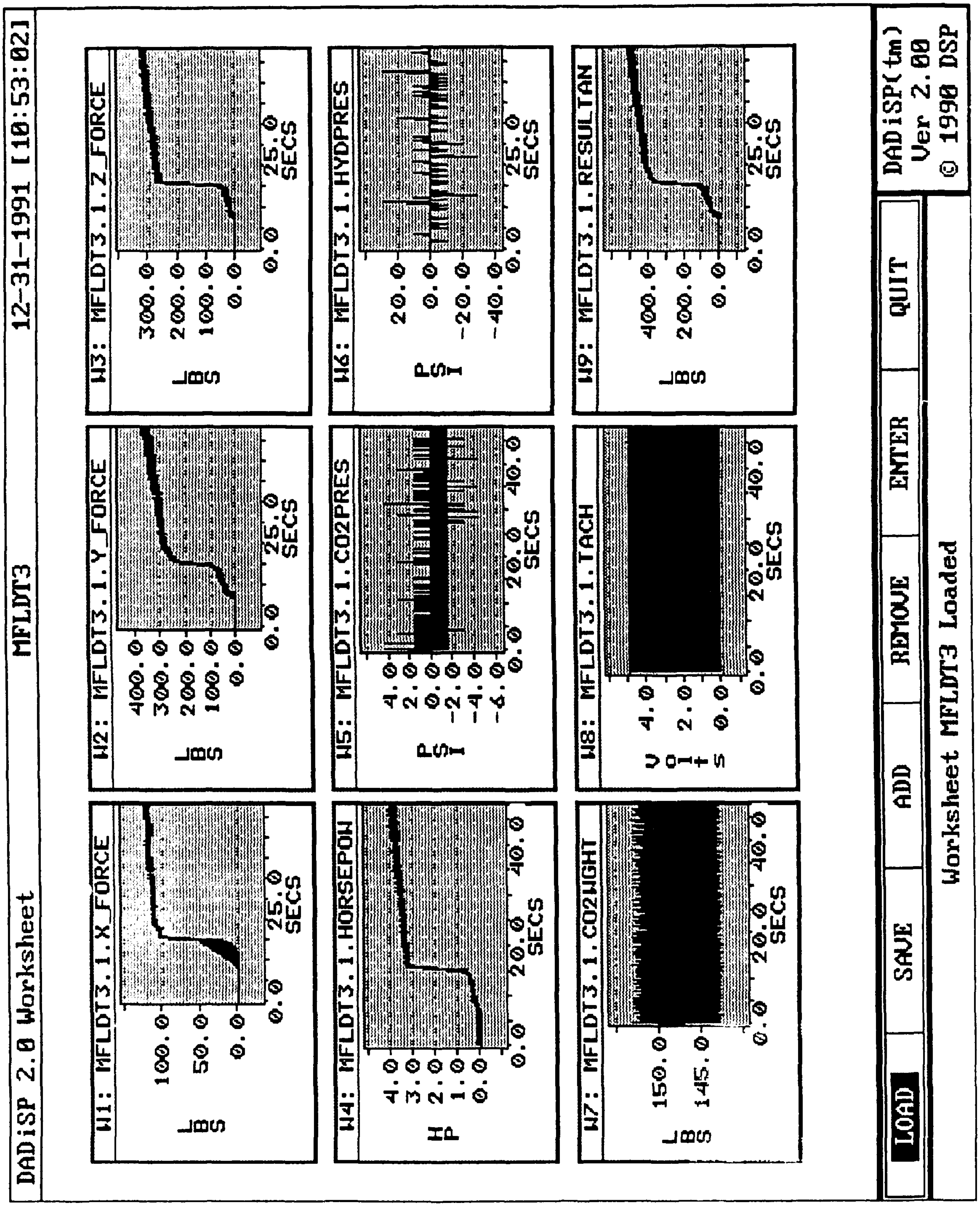
DADiSP 2.0 Worksheet
MFLDT3
12-31-1991 [10:53:02]
W1: MFLDT3.1.X_FORCE
W2: MFLDT3.1.Y_FORCE
W3: MFLDT3.1.Z_FORCE
W4: MFLDT3.1.HORSEPOW
W5: MFLDT3.1.CO2PRES
W6: MFLDT3.1.HYDPRES
W7: MFLDT3.1.CO2WGHT
W8: MFLDT3.1.TACH
W9: MFLDT3.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
RDMOVE
ENTER
QUIT
Worksheet MFLDT3 Loaded
DADiSP(tm)
Ver 2.00
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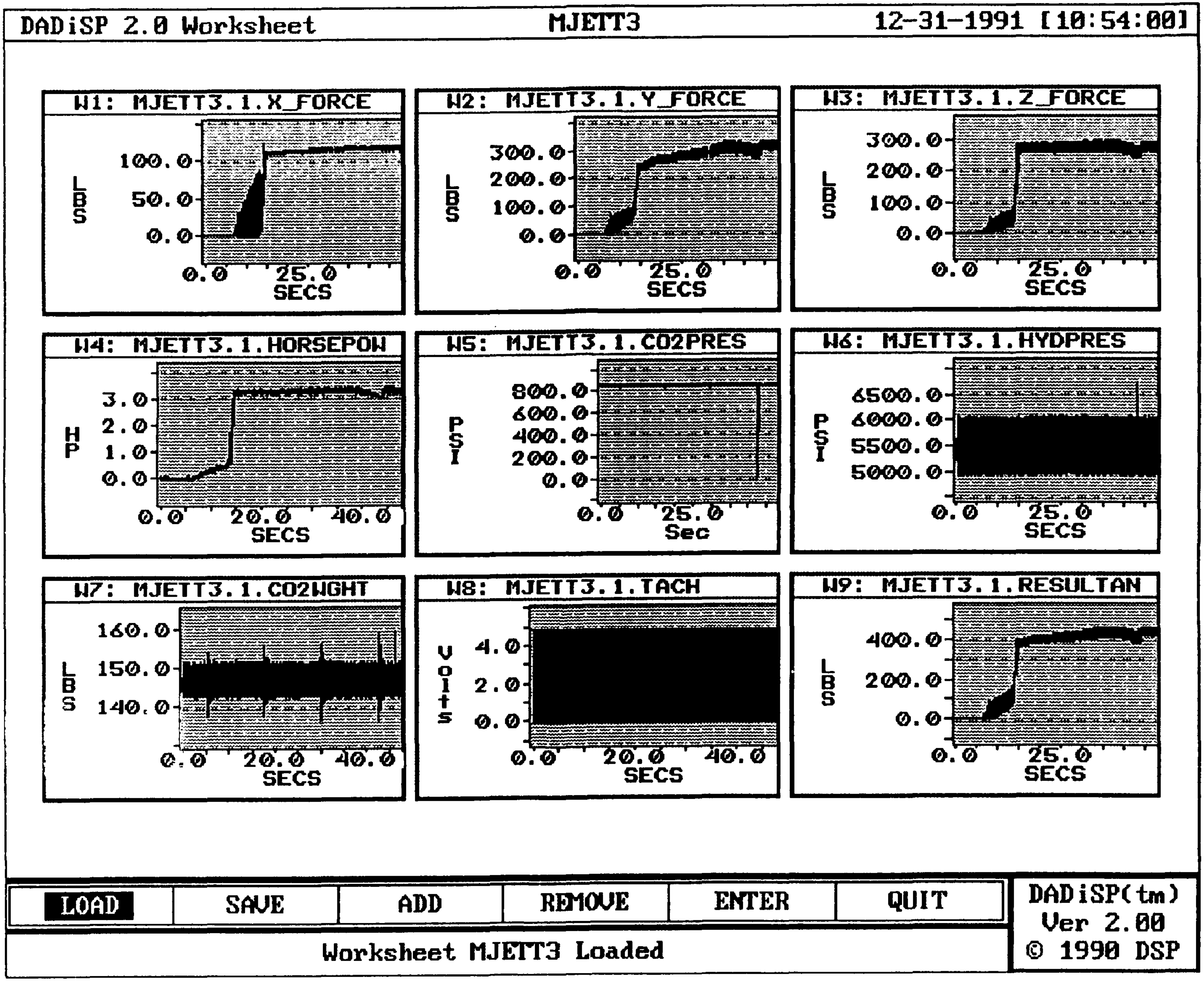

DADiSP 2.0 Worksheet
MJETT3
12-31-1991 [10:54:00]
W1: MJETT3.1.X_FORCE
LBS
100.0
50.0
0.0
0.0
25.0
SECS
W2: MJETT3.1.Y_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
25.0
SECS
W3: MJETT3.1.Z_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
25.0
SECS
W4: MJETT3.1.HORSEPOW
HP
3.0
2.0
1.0
0.0
0.0
20.0
40.0
SECS
W5: MJETT3.1.CO2PRES
PSI
800.0
600.0
400.0
200.0
0.0
0.0
25.0
Sec
W6: MJETT3.1.HYDPRES
PSI
6500.0
6000.0
5500.0
5000.0
0.0
25.0
SECS
W7: MJETT3.1.CO2WGHT
LBS
160.0
150.0
140.0
0.0
20.0
40.0
SECS
W8: MJETT3.1.TACH
Volts
4.0
2.0
0.0
0.0
20.0
40.0
SECS
W9: MJETT3.1.RESULTAN
LBS
400.0
200.0
0.0
0.0
25.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
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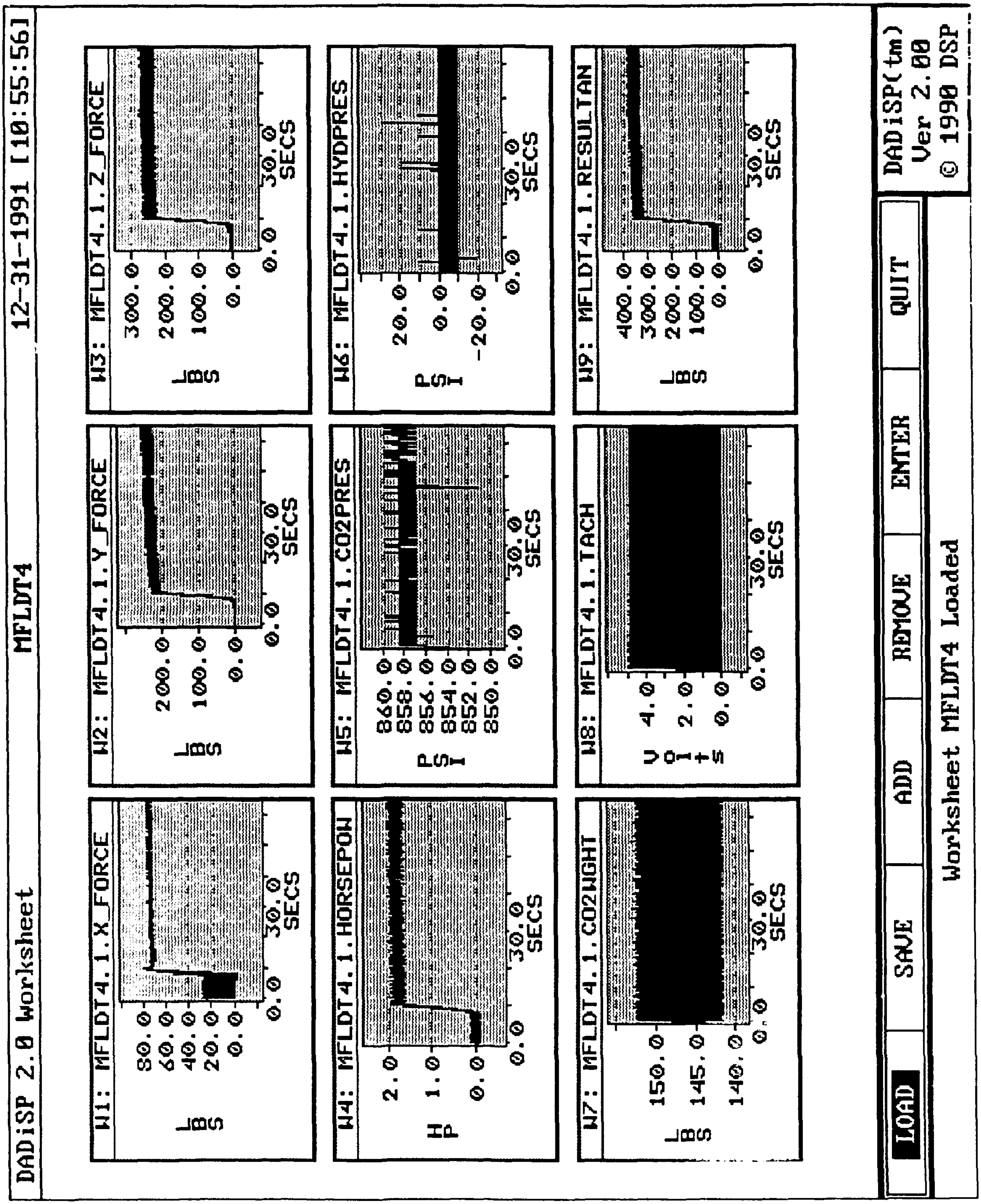
Worksheet MJETT3 Loaded


DADiSP 2.0 Worksheet
MFLDT4
12-31-1991 [10:55:56]
W1: MFLDT4.1.X_FORCE
W2: MFLDT4.1.Y_FORCE
W3: MFLDT4.1.Z_FORCE
W4: MFLDT4.1.HORSEPOW
W5: MFLDT4.1.CO2PRES
W6: MFLDT4.1.HYDPRES
W7: MFLDT4.1.CO2WGHT
W8: MFLDT4.1.TACH
W9: MFLDT4.1.RESULTAN
LBS
HP
PSI
Volts
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
Worksheet MFLDT4 Loaded
DADiSP(tm)
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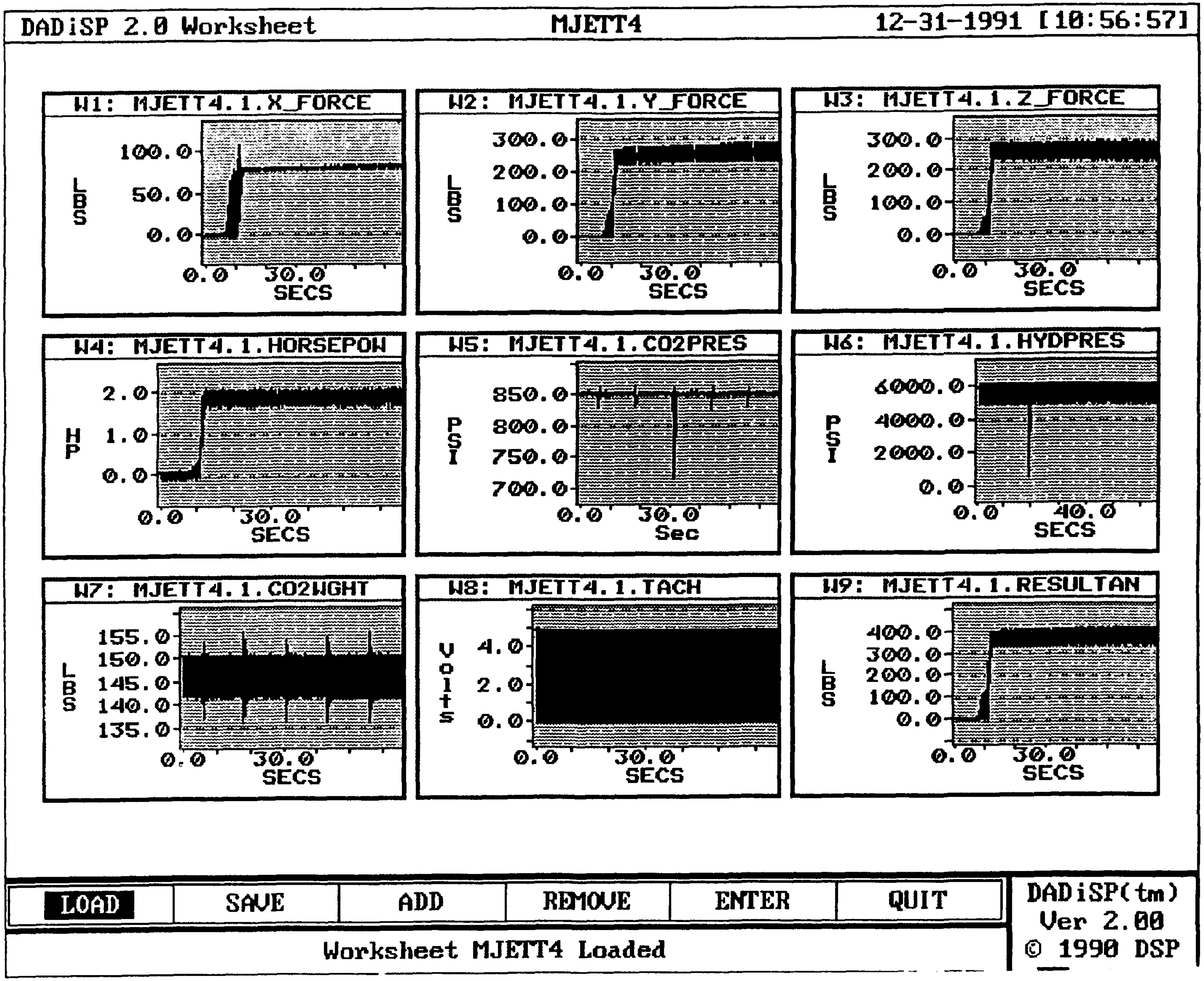
DADiSP 2.0 Worksheet
MJETT4
12-31-1991 [10:56:57]
W1: MJETT4.1.X_FORCE
LBS
100.0
50.0
0.0
0.0
30.0
SECS
W2: MJETT4.1.Y_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
30.0
SECS
W3: MJETT4.1.Z_FORCE
LBS
300.0
200.0
100.0
0.0
0.0
30.0
SECS
W4: MJETT4.1.HORSEPOW
HP
2.0
1.0
0.0
0.0
30.0
SECS
W5: MJETT4.1.CO2PRES
PSI
850.0
800.0
750.0
700.0
0.0
30.0
Sec
W6: MJETT4.1.HYDPRES
PSI
6000.0
4000.0
2000.0
0.0
0.0
40.0
SECS
W7: MJETT4.1.CO2WGHT
LBS
155.0
150.0
145.0
140.0
135.0
0.0
30.0
SECS
W8: MJETT4.1.TACH
Volts
4.0
2.0
0.0
0.0
30.0
SECS
W9: MJETT4.1.RESULTAN
LBS
400.0
300.0
200.0
100.0
0.0
0.0
30.0
SECS
LOAD
SAVE
ADD
REMOVE
ENTER
QUIT
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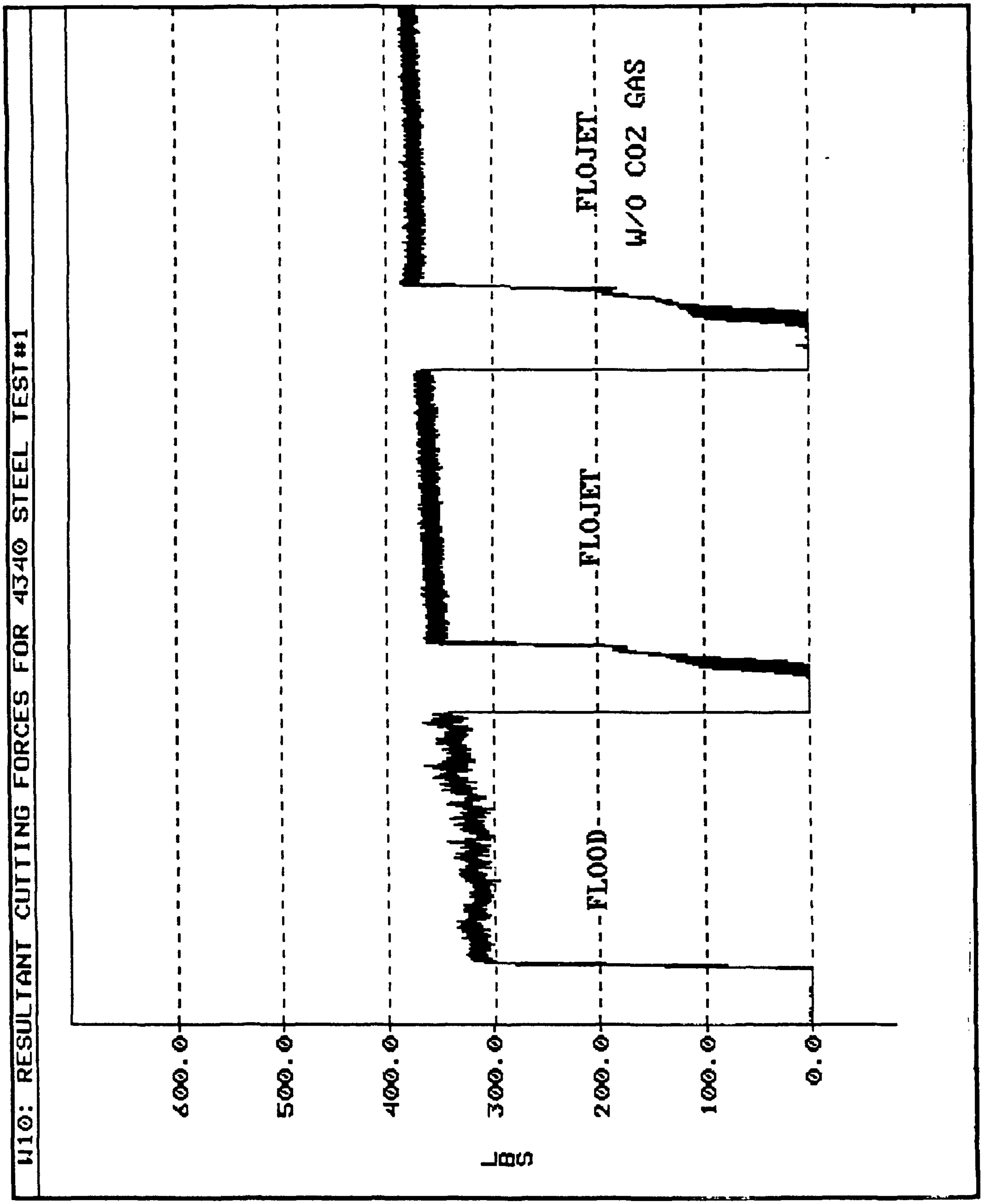
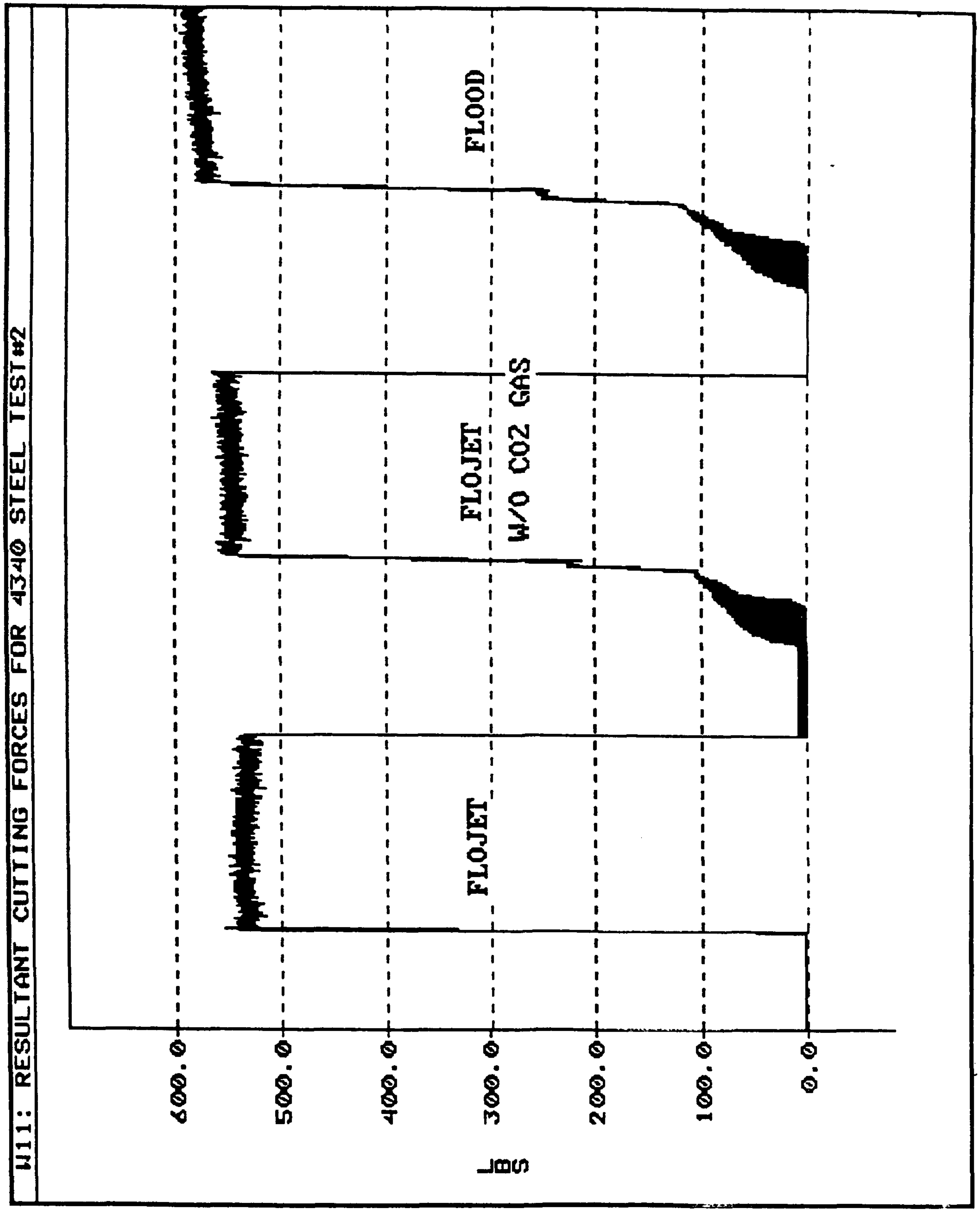
Worksheet MJETT4 Loaded

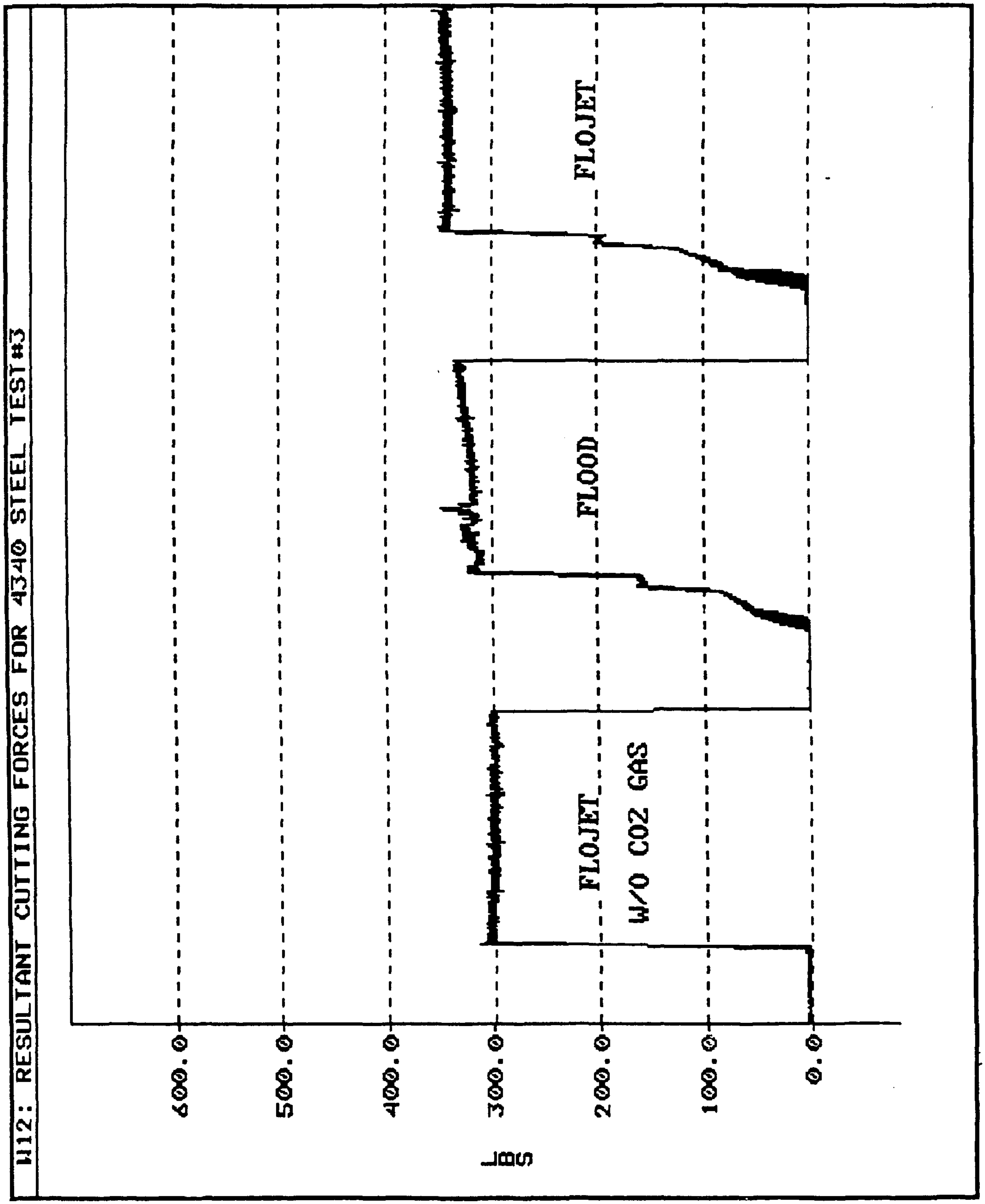
APPENDIX E

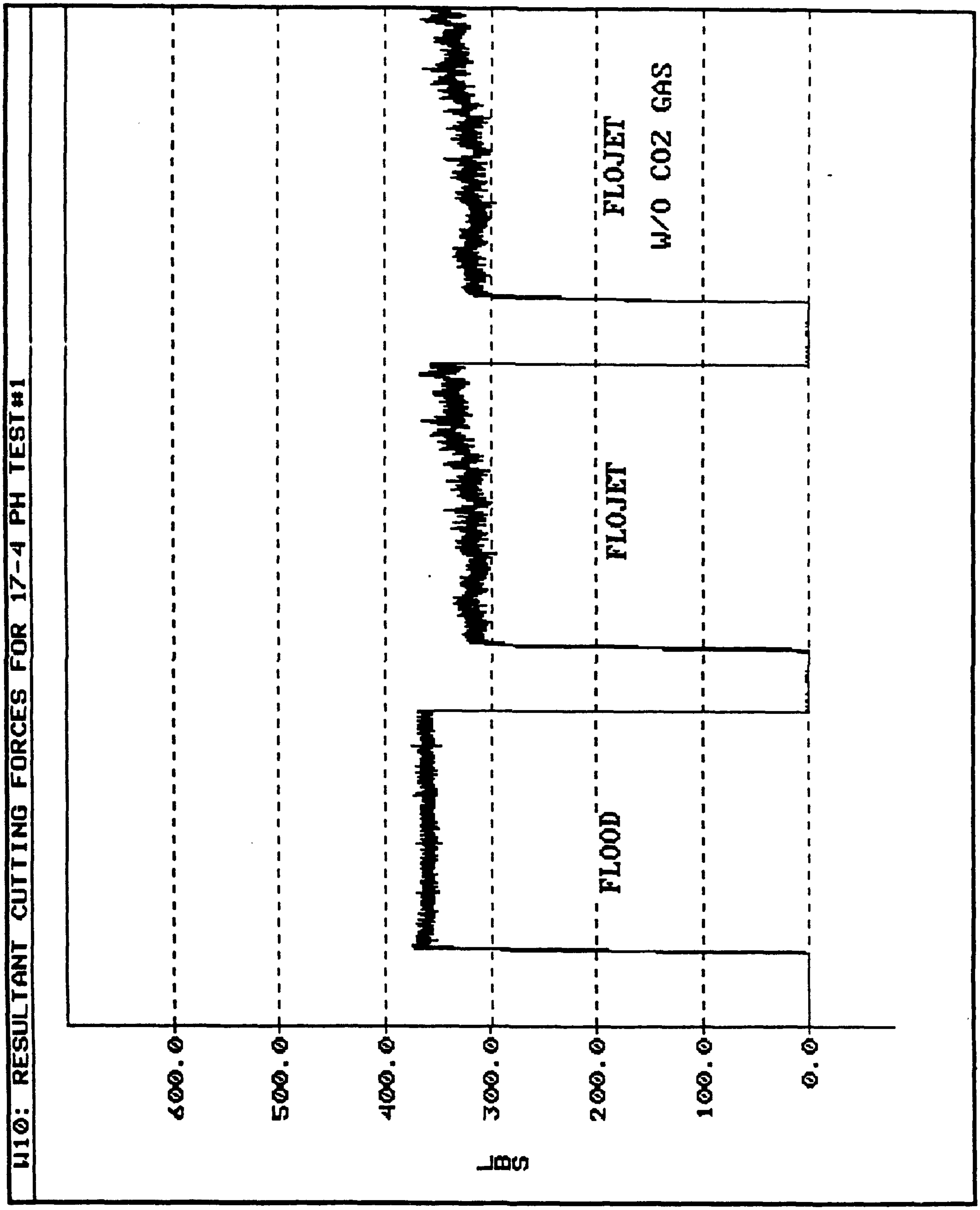
TEST DATA

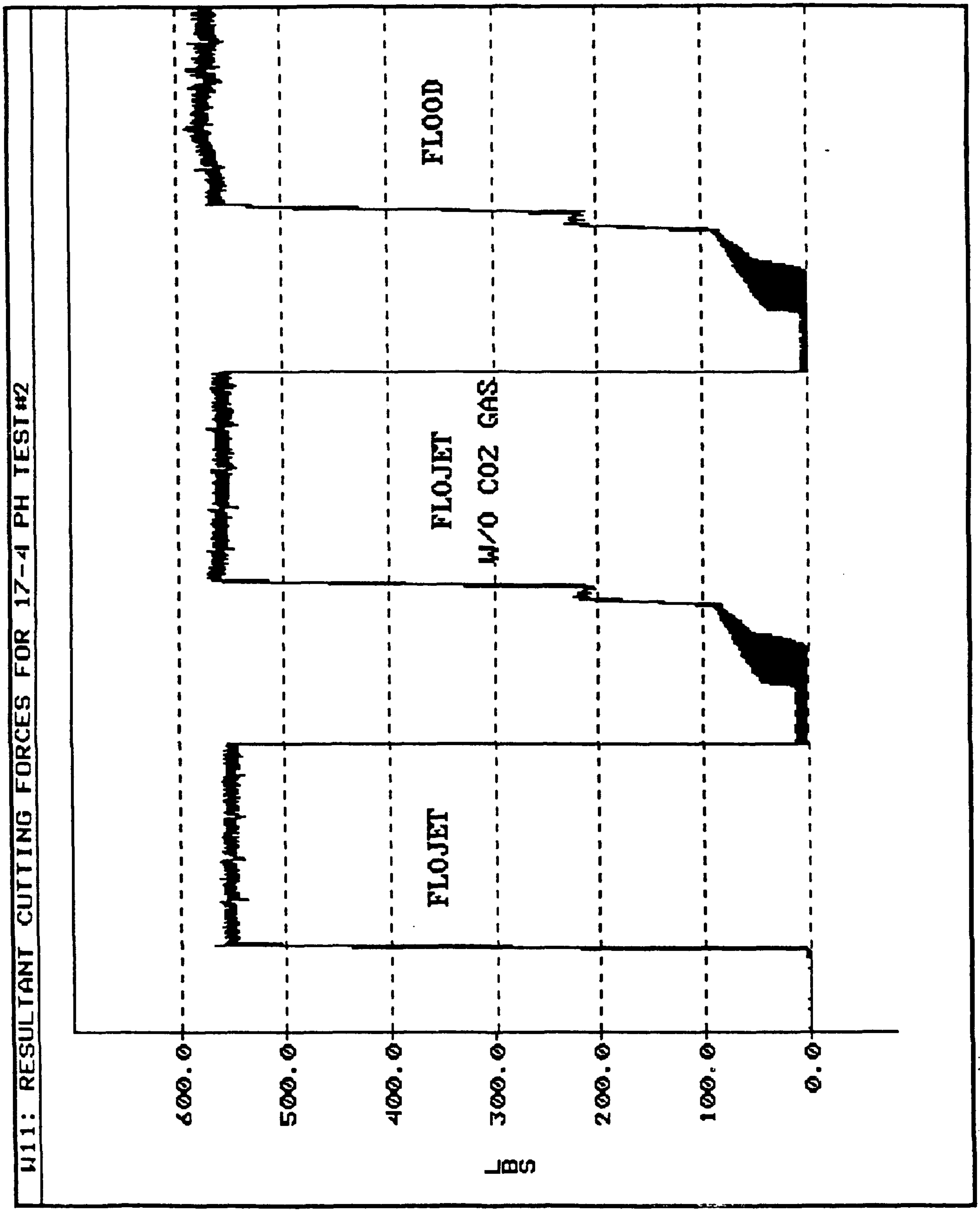
RESULTANT CUTTING FORCES COMPARING FLOOD, *flojet*, *flojet* WITHOUT CO_2

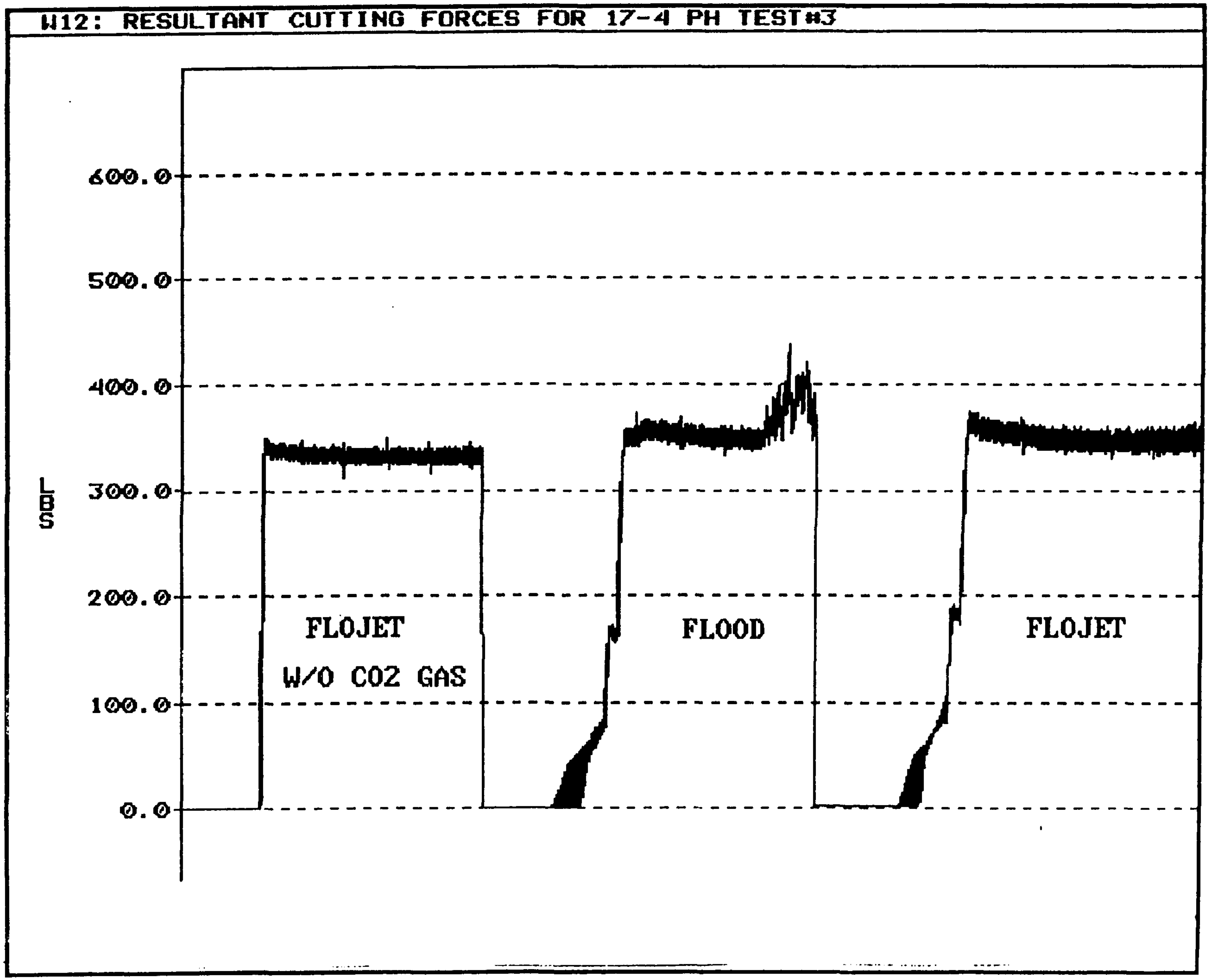

W10: RESULTANT CUTTING FORCES FOR 4340 STEEL TEST#1
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOOD
FLOJET
FLOJET
W/O CO2 GAS

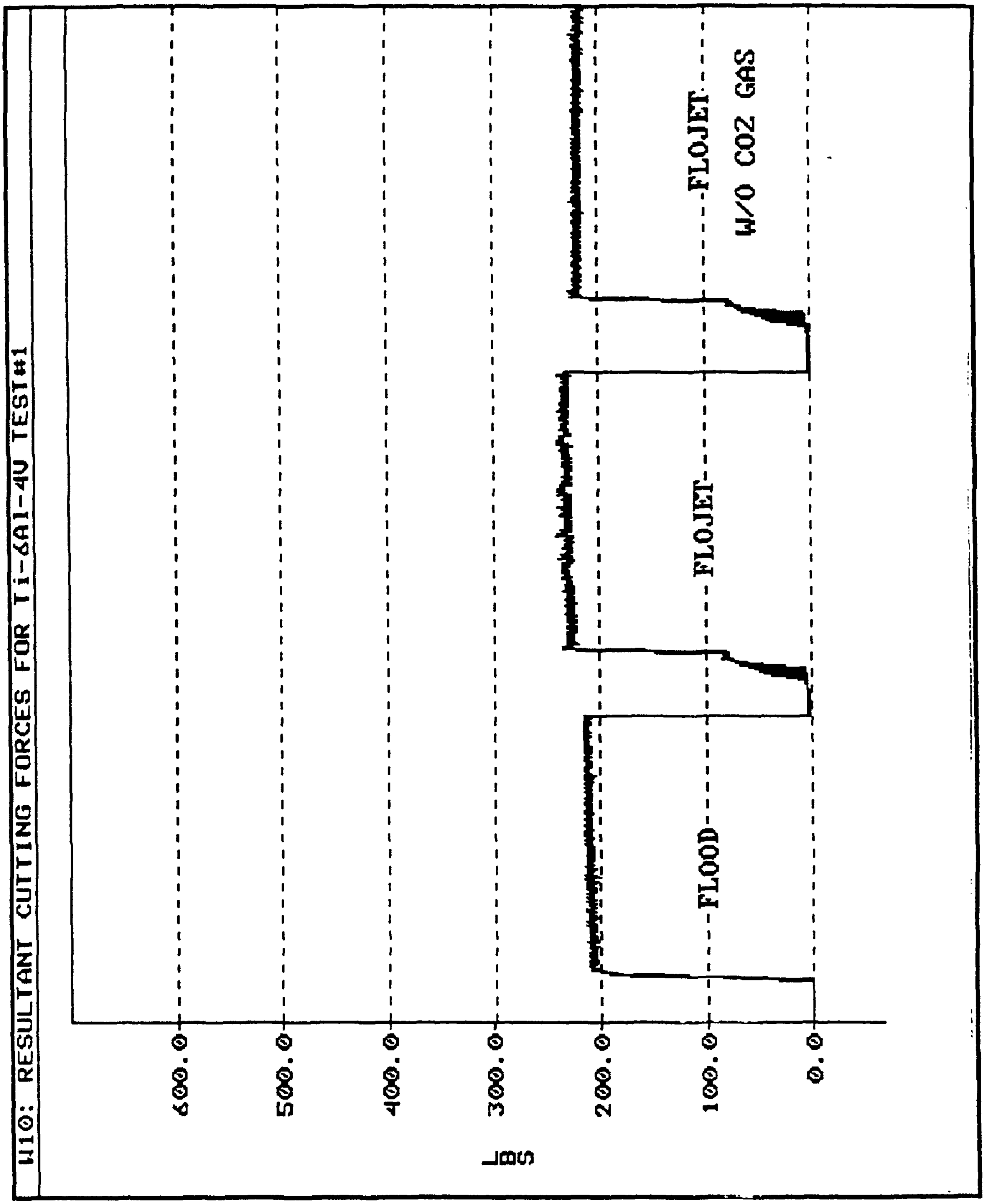

W11: RESULTANT CUTTING FORCES FOR 4340 STEEL TEST#2
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOJET
FLOJET
W/O CO2 GAS
FLOOD


W12: RESULTANT CUTTING FORCES FOR 4340 STEEL TEST#3
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOJET
W/O CO2 GAS
FLOOD
FLOJET


W10: RESULTANT CUTTING FORCES FOR 17-4 PH TEST#1
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOOD
FLOJET
FLOJET
W/O CO2 GAS

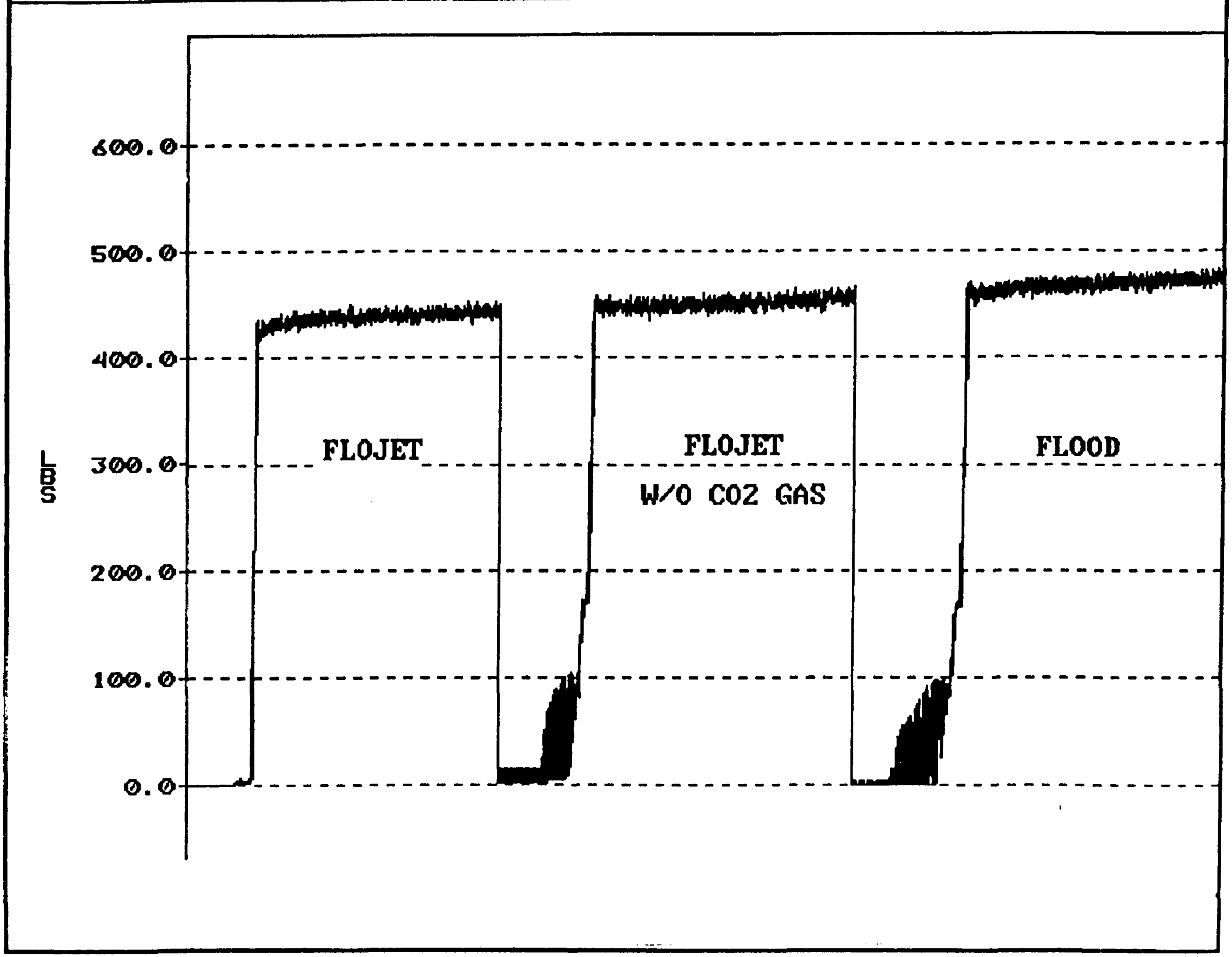

W11: RESULTANT CUTTING FORCES FOR 17-4 PH TEST #2
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOJET
FLOJET
W/O CO2 GAS
FLOOD

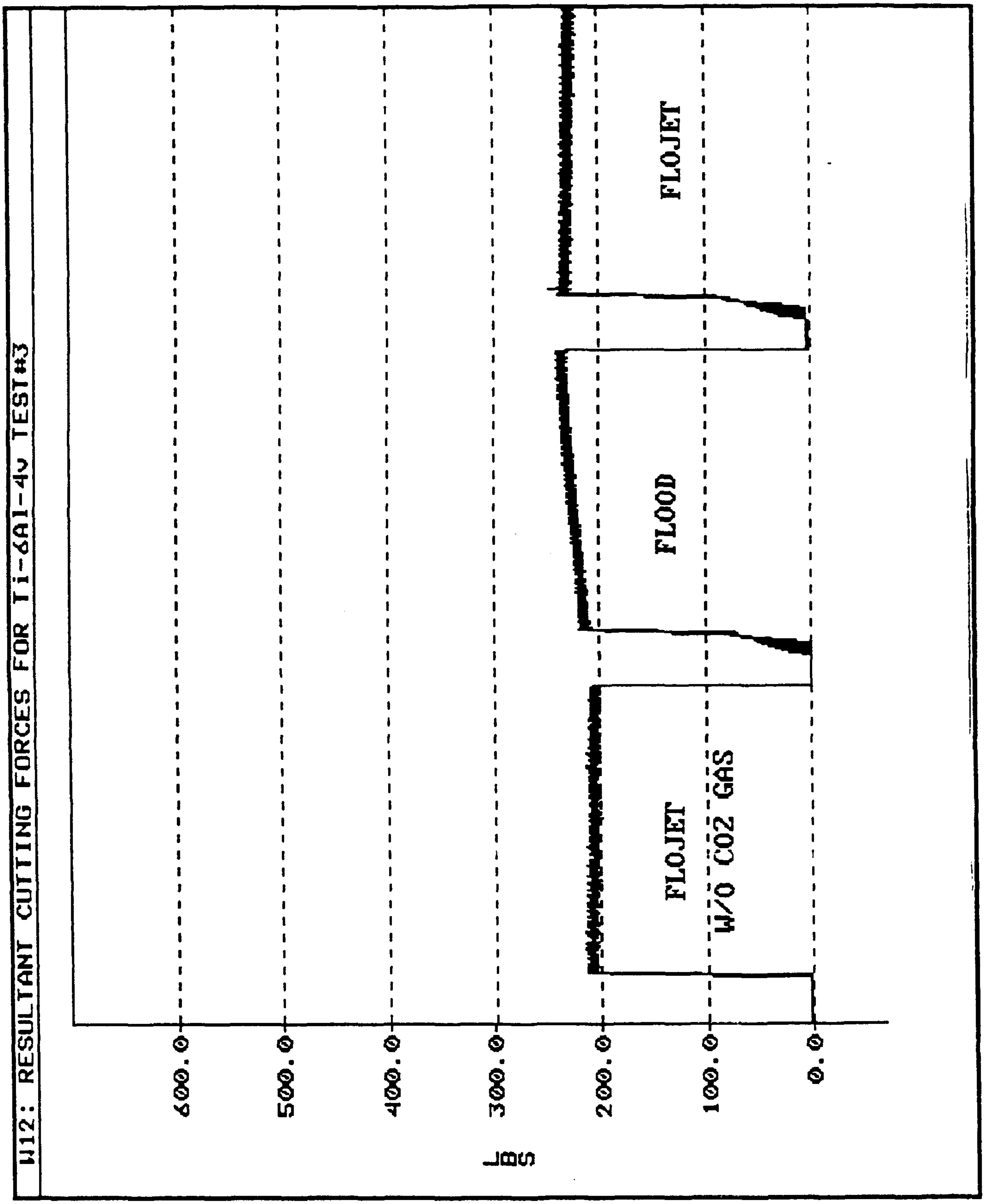

W12: RESULTANT CUTTING FORCES FOR 17-4 PH TEST#3
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOJET
W/O CO2 GAS
FLOOD
FLOJET

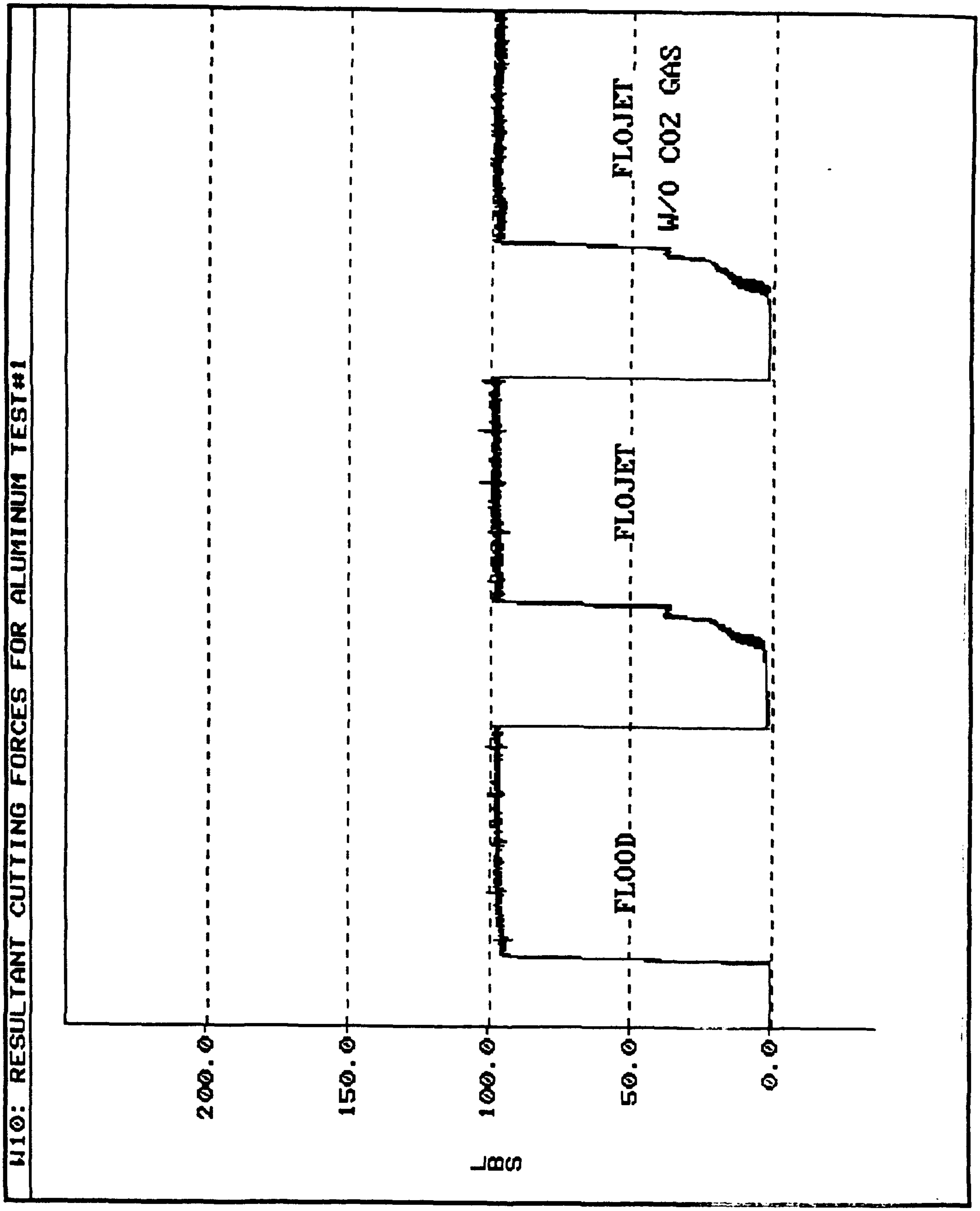


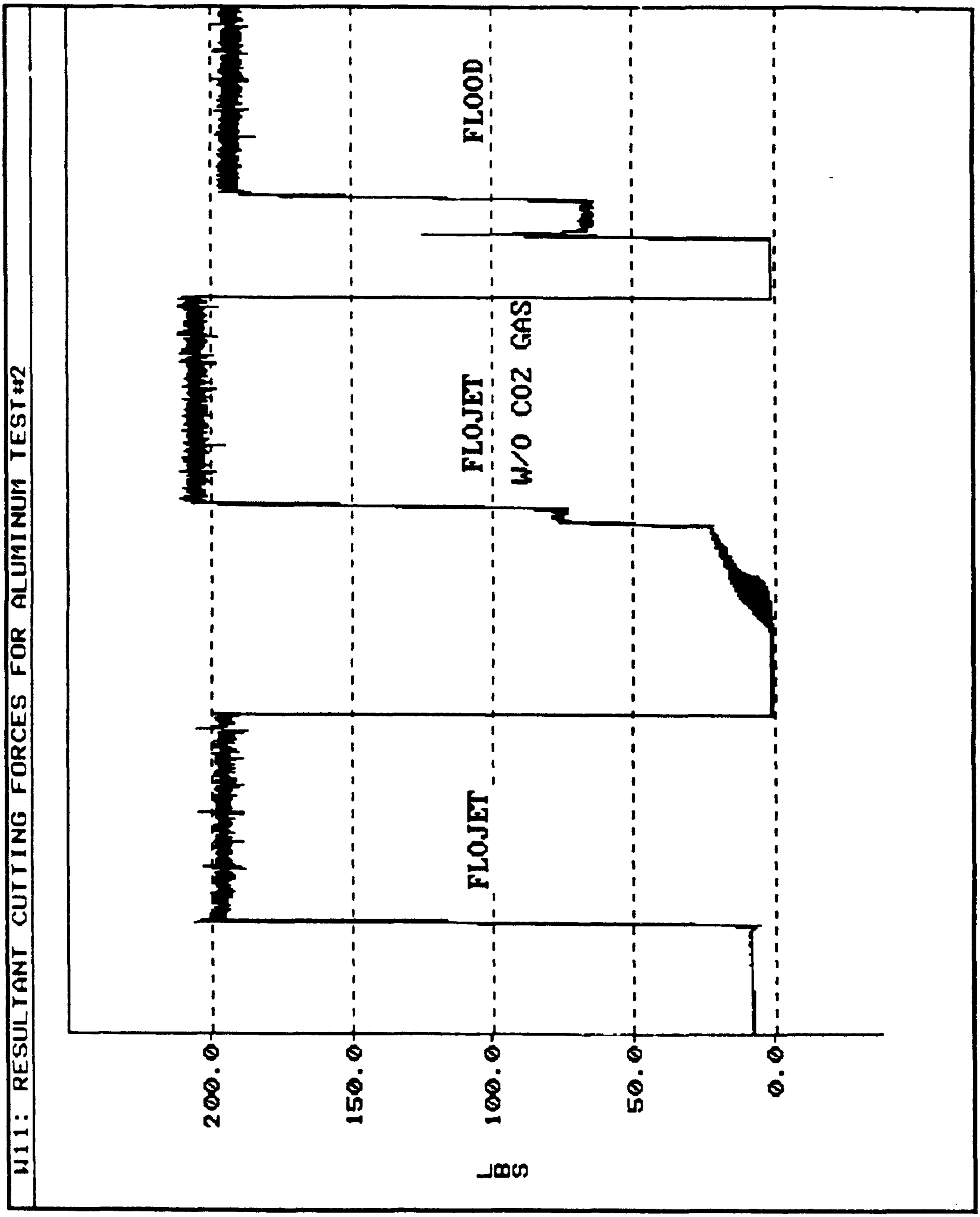
W10: RESULTANT CUTTING FORCES FOR Ti-6Al-4V TEST#1
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOOD
FLOJET
FLOJET
W/O CO2 GAS

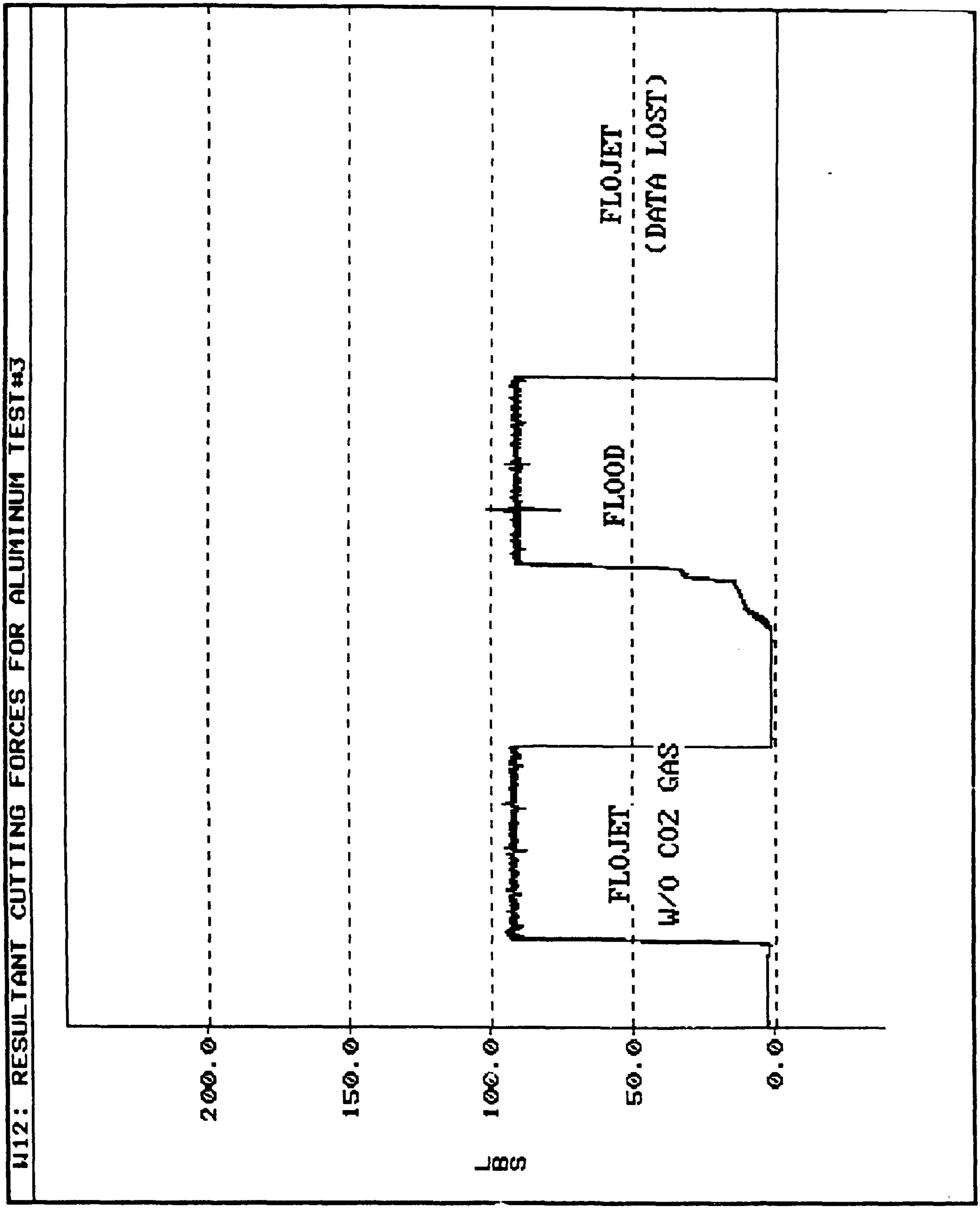
W11: RESULTANT CUTTING FORCES FOR Ti-6Al-4V TEST#2

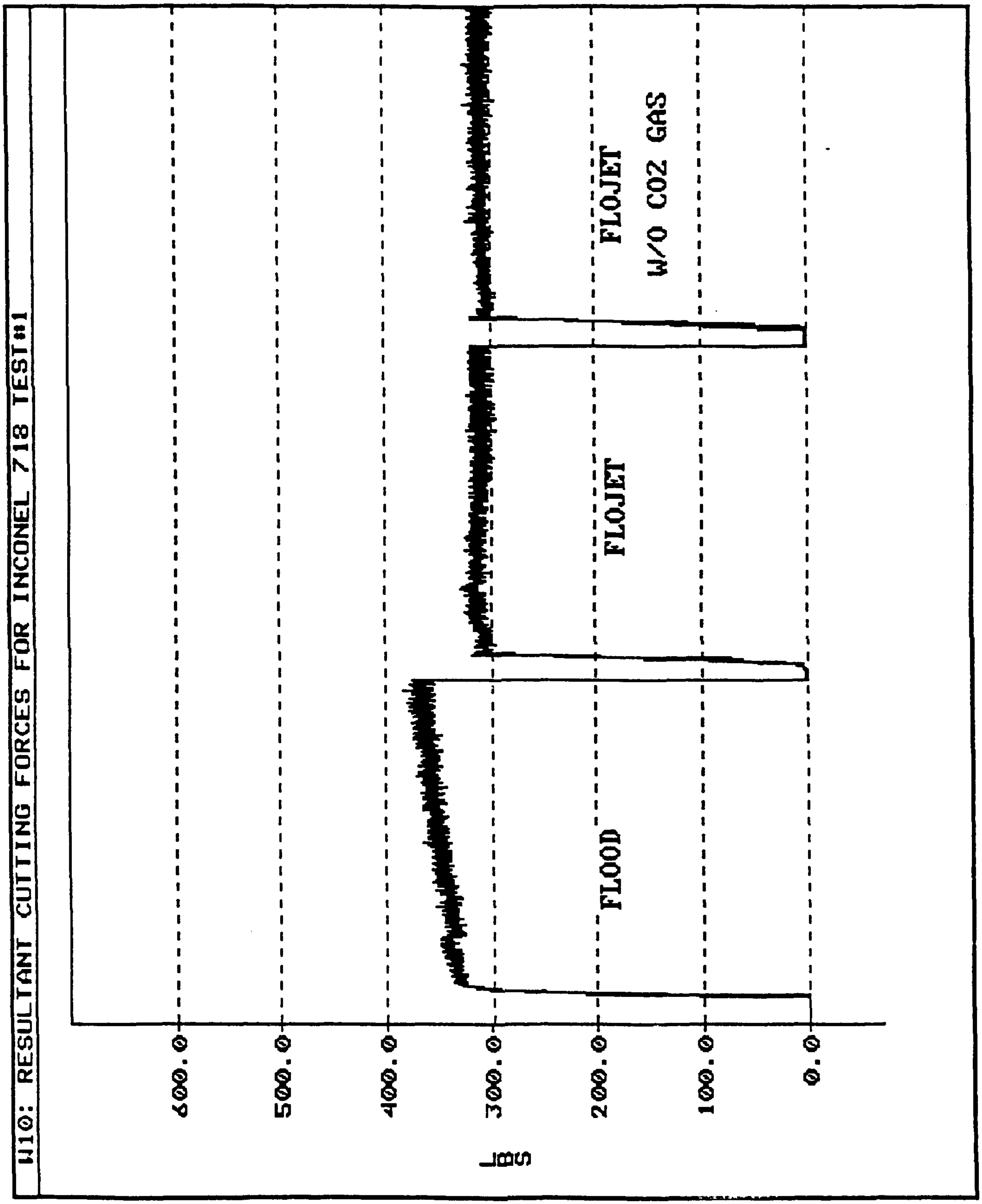


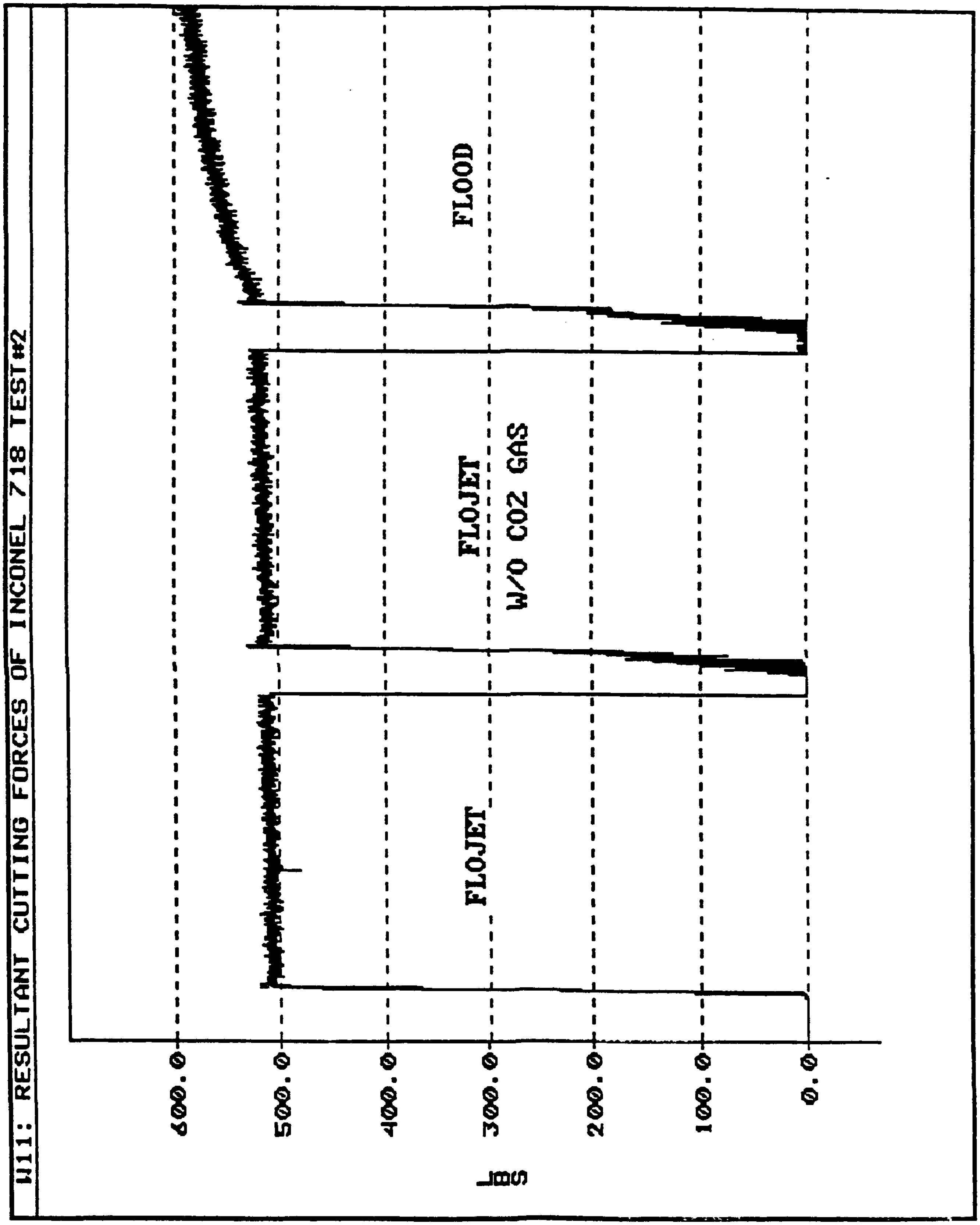

W12: RESULTANT CUTTING FORCES FOR Ti-6Al-4V TEST#3
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOJET
W/O CO2 GAS
FLOOD
FLOJET

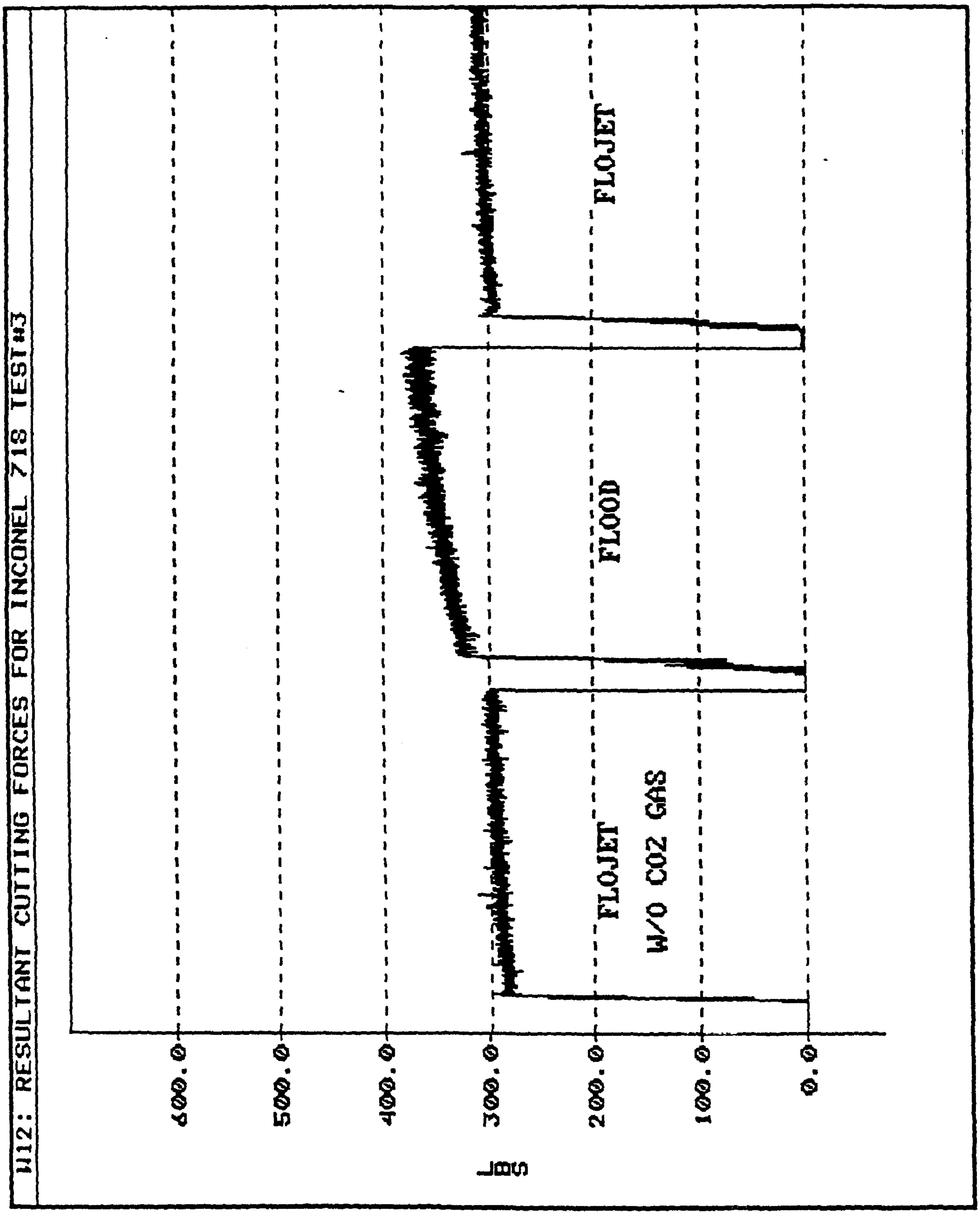

W10: RESULTANT CUTTING FORCES FOR ALUMINUM TEST#1
LBS
200.0
150.0
100.0
50.0
0.0
FLOOD
FLOJET
FLOJET
W/O CO2 GAS

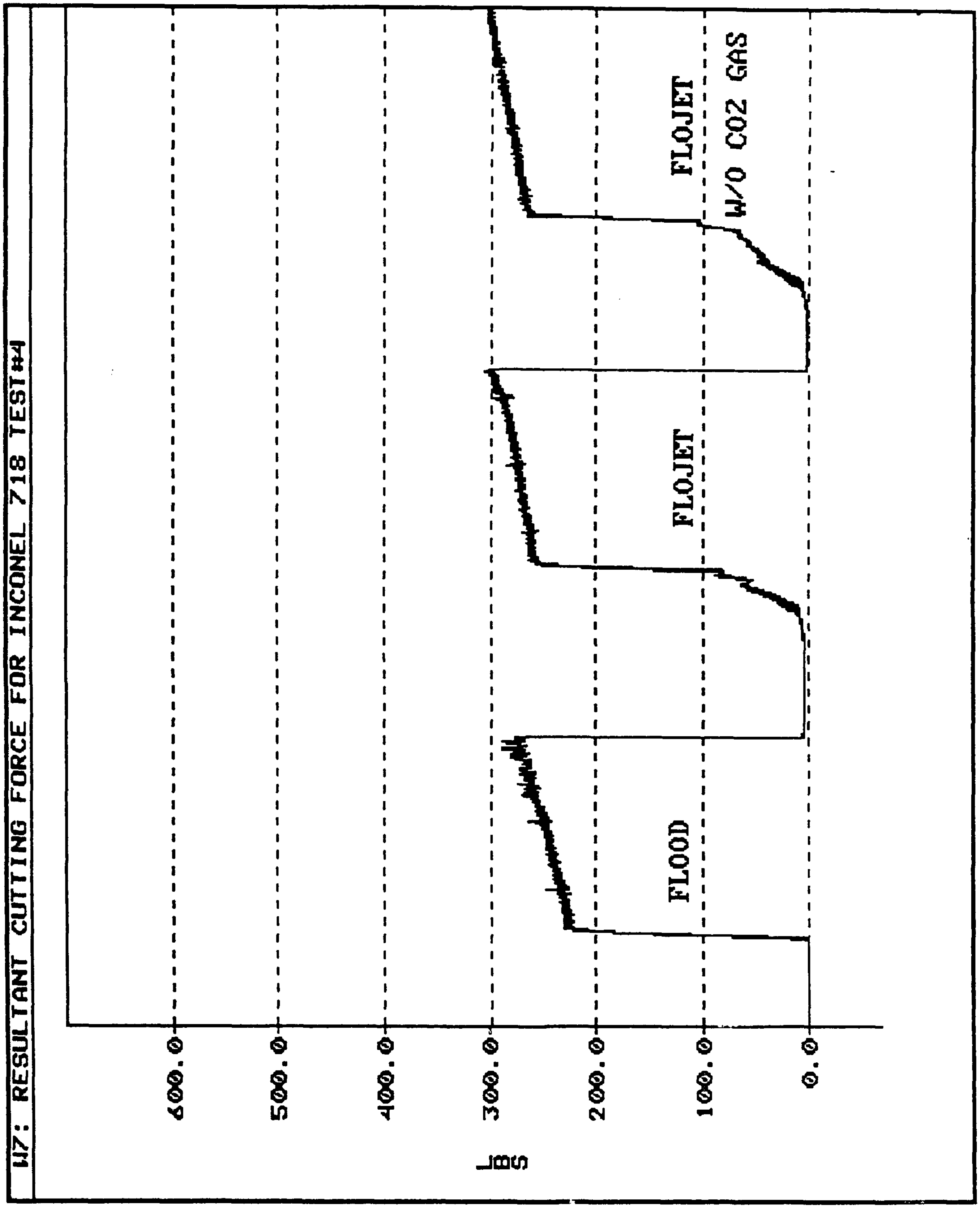

W11: RESULTANT CUTTING FORCES FOR ALUMINUM TEST #2
LBS
200.0
150.0
100.0
50.0
0.0
FLOJET
FLOJET
W/O CO2 GAS
FLOOD


W12: RESULTANT CUTTING FORCES FOR ALUMINUM TEST#3
LBS
200.0
150.0
100.0
50.0
0.0
FLOJET
W/O CO2 GAS
FLOOD
FLOJET
(DATA LOST)


W10: RESULTANT CUTTING FORCES FOR INCONEL 718 TEST#1
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOOD
FLOJET
FLOJET
W/O CO2 GAS

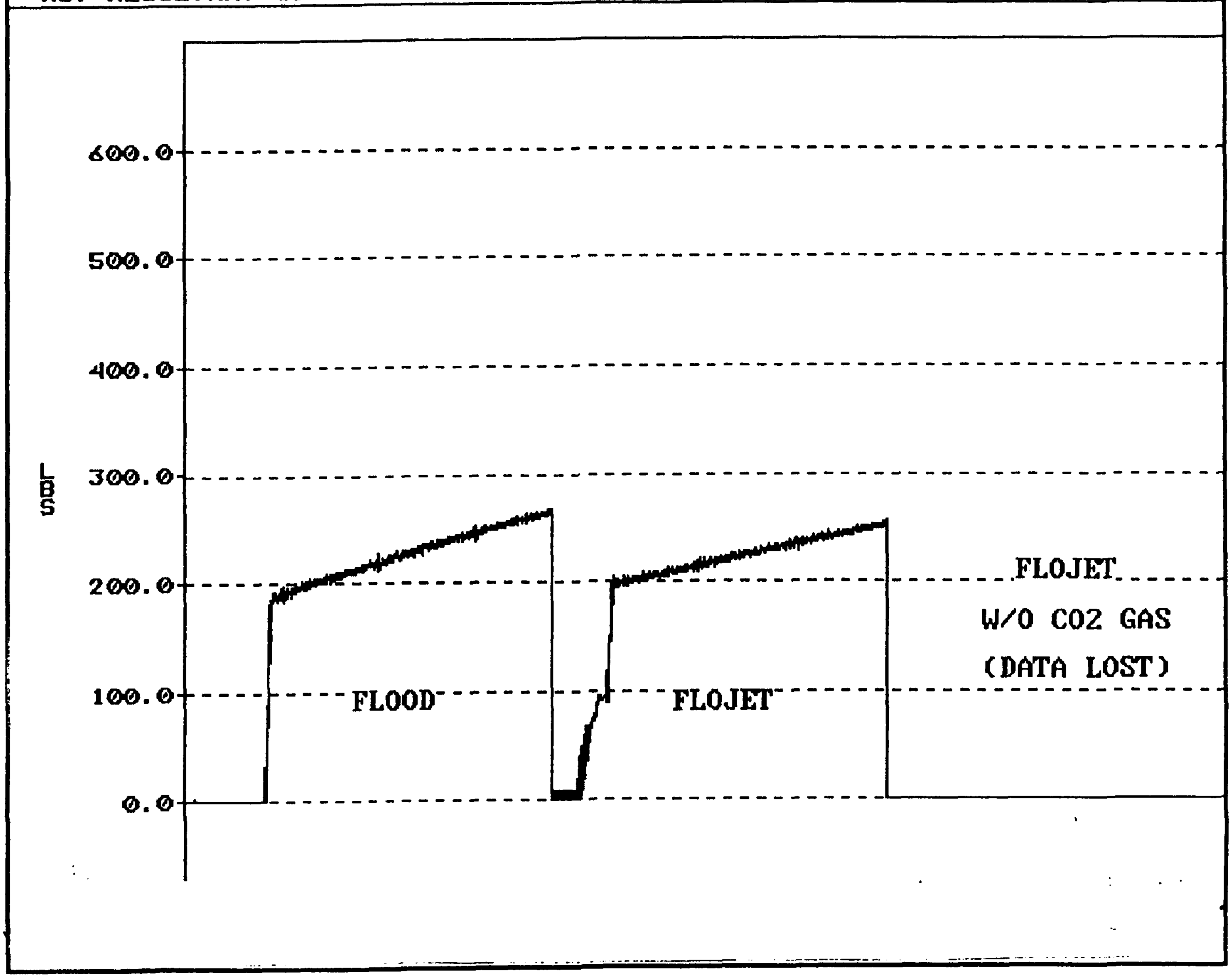

W11: RESULTANT CUTTING FORCES OF INCONEL 718 TEST#2
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOJET
FLOJET
W/O CO2 GAS
FLOOD

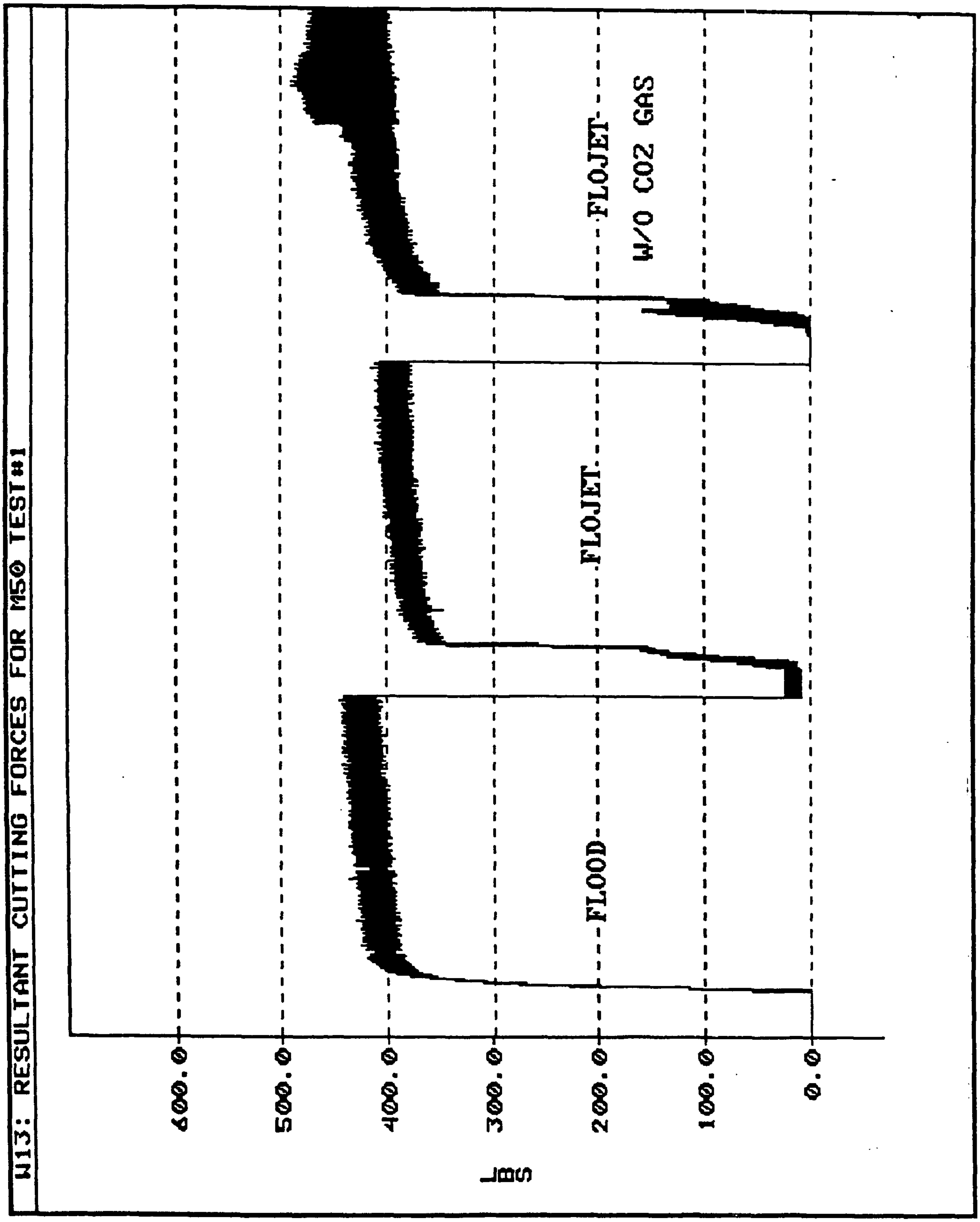

1112: RESULTANT CUTTING FORCES FOR INCONEL 718 TEST#3
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOJET
W/O CO2 GAS
FLOOD
FLOJET



W7: RESULTANT CUTTING FORCE FOR INCONEL 718 TEST#4
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOOD
FLOJET
FLOJET
W/O CO2 GAS

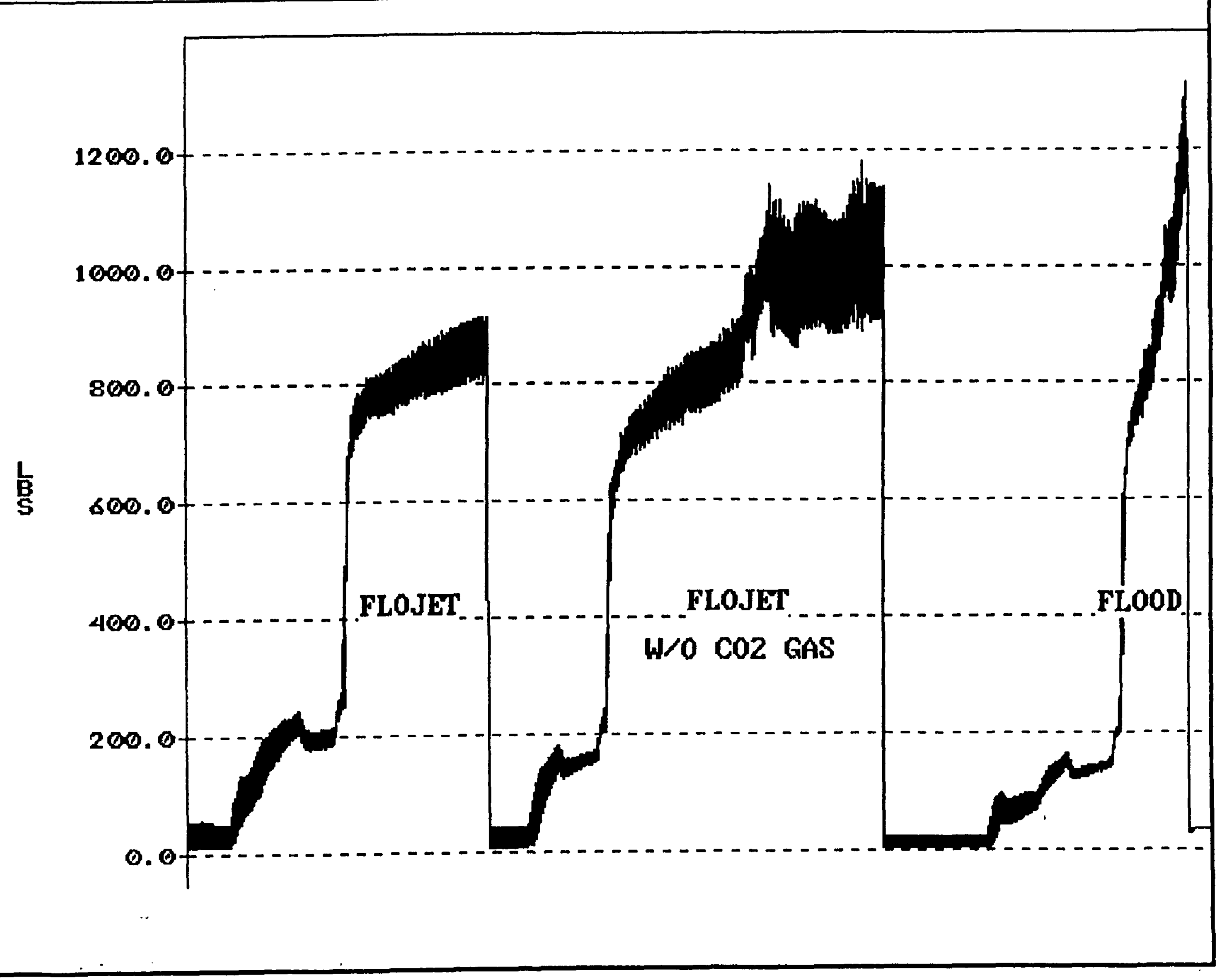
W8: RESULTANT CUTTING FORCES FOR INCONEL 718 TEST#5

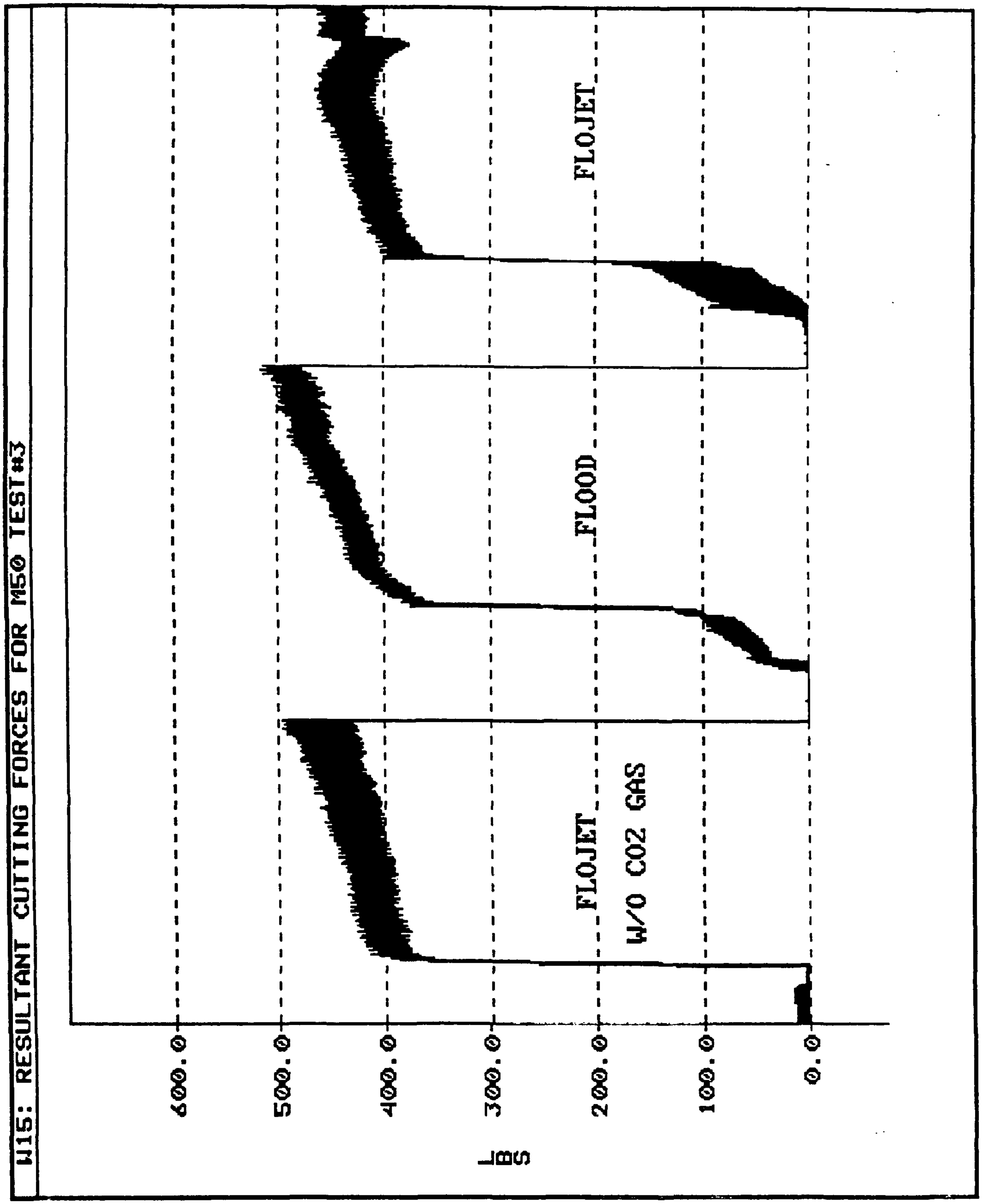


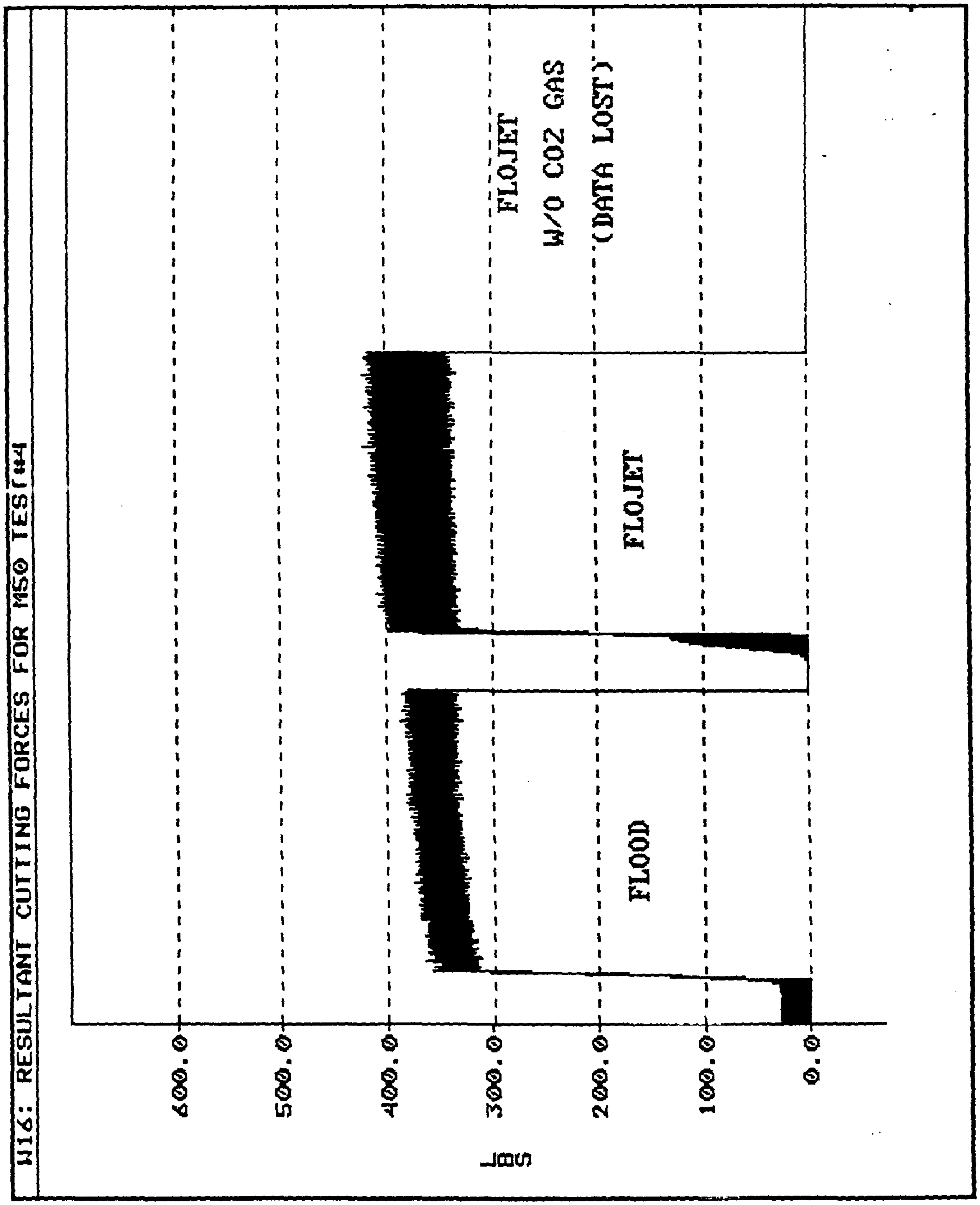


W13: RESULTANT CUTTING FORCES FOR M50 TEST#1
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOOD
FLOJET
FLOJET
W/O CO2 GAS

W14: RESULTANT CUTTING FORCES FOR M50 TEST#2




W15: RESULTANT CUTTING FORCES FOR M50 TEST#3
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOJET
W/O CO2 GAS
FLOOD
FLOJET


W16: RESULTANT CUTTING FORCES FOR M50 TEST#4
LBS
600.0
500.0
400.0
300.0
200.0
100.0
0.0
FLOOD
FLOJET
FLOJET
W/O CO2 GAS
(DATA LOST)

APPENDIX F

POST-CUT MATERIAL ANALYSIS

LABORATORY REPORT

TO: Institute of Advanced Manufacturing Sciences
Attn: Mike Finn
1111 Edison Drive
Cincinnati OH 45216

NUMBER: 2998-55349-1
DATE: January 20, 1992
AUTHORIZATION:

PROJECT: Surface Integrity Study of Twelve Machined Samples

1. Introduction

Six bars, each of a different alloy composition and containing two test surfaces, were submitted to Metcut for surface integrity evaluation. A metallurgical section was obtained perpendicular to the machining lay from each of the Flojet and Flood test surfaces designated by IAMS and metallographically prepared utilizing techniques for achieving optimum edge retention. The specimens were viewed in the unetched and etched conditions at magnifications ranging from 400X to 1000X. Microhardness surveys using a Knoop indenter and 100 gram load were then obtained to detect hardness gradients.

Observations and test results are presented as follows:

2. Metallography

Sample Ident.	Test Condition	Observations/Surface Features (@ 1000X)
7075 Al Alloy	Flojet	Generally smooth surface with no evidence of microcracks. Small isolated laps, less than .0003", were noted. Etching revealed a discontinuous plastically deformed layer, less than .001" in depth. Reference Figure 1A.
	Flood	Same as above. Reference Figure 1B.
Ti-6Al-4V	Flojet	Generally smooth surface with no evidence of microcracks. Small isolated laps, less than .0003", were noted. Etching revealed a discontinuous layer of plastic deformation of .0005" maximum depth. Reference Figure 2A.
	Flood	Same as above. Reference Figure 2B.

Luciano R. Gatto, Manager
Metallography & Failure Analysis
fw

Thomas D. DiLullo
Chief Metallographer

Sample Ident.	Test Condition	Observations/Surface Features (@ 1000X)
AISI 4340 Steel	Flojet	Generally smooth surface with minute surface pits. No microcracks or laps observed. Etching revealed a thin continuous layer of plastic deformation measuring typically .0003" in depth. Reference Figure 3A.
	Flood	Same as above. Reference Figure 3B.
17-4 PH Stainless	Flojet	Generally smooth surface with no evidence of microcracks or laps. A continuous layer of plastic deformation, less than .001", was observed. Reference Figure 4A.
	Flood	Same as above. Reference Figure 4B.
Inconel	Flojet	Generally smooth surface with no evidence of microcracks or laps. A continuous plastically deformed layer, less than .0005", was observed. Reference Figure 5A.
	Flood	Same as above. Reference Figure 5B.
M50 Tool Steel	Flojet	Generally smooth surface with no evidence of microcracks or laps. A thin discontinuous white layer, less than .0001", of presumably untempered martensite was noted. Reference Figure 6A.
	Flood	Same as above. Reference Figure 6B.

3. Microhardness Surveys

Knoop 100 gram microhar 1ness readings were obtained at a depth of .001", .005" and .010" beneath the machined surface. With the exception of the AISI 4340 material where a slight surface softening of about 3-4 HRC points was detected on both the Flojet and Flood conditions, the rest of the samples revealed no notable hardness gradients. Microhardness data is presented in Table I.

TABLE I

Microhardness Surveys *

7075 Al Alloy

Distance from Surface (in.)	Flojet Knoop (100g)	Flojet HRB (conv)	Flood Knoop (100g)	Flood HRB (conv)
.001	169	81.5	170	82.0
.005	168	81.5	167	81.0
.010	171	82.0	171	82.0

Ti-6Al-4V

Distance from Surface (in.)	Flojet Knoop (100g)	Flojet HRC (conv)	Flood Knoop (100g)	Flood HRC (conv)
.001	369	37.0	395	39.5
.005	400	40.0	410	41.0
.010	379	38.0	396	39.5

AISI 4340

Distance from Surface (in.)	Flojet Knoop (100g)	Flojet HRC (conv)	Flood Knoop (100g)	Flood HRC (conv)
.001	410	41.0	408	40.5
.005	433	43.0	426	42.0
.010	452	44.0	457	44.5

17-4PH

Distance from Surface (in.)	Flojet Knoop (100g)	Flojet HRC (conv)	Flood Knoop (100g)	Flood HRC (conv)
.001	419	41.0	424	42.0
.005	420	41.5	416	41.0
.010	416	41.0	424	42.0

* Note: Values at .001 and .005 represent an average of 3 to 6 readings.

TABLE I continued

Microhardness Surveys

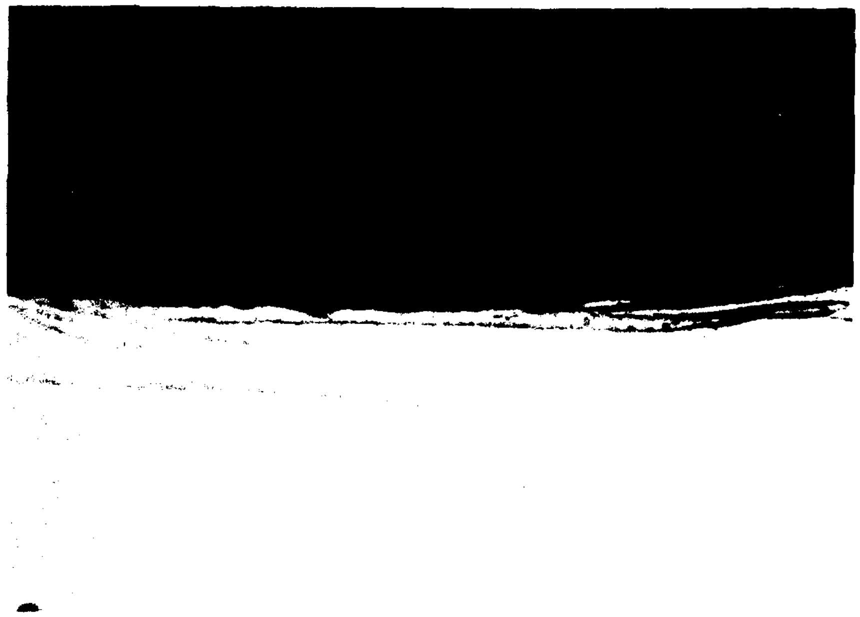
Inconel

Distance from Surface (in.)	Flojet Knoop (100g)	Flojet HRC (conv)	Flood Knoop (100g)	Flood HRC (conv)
.001	488	46.0	492	46.5
.005	488	46.0	498	47.0
.010	493	46.5	505	47.5

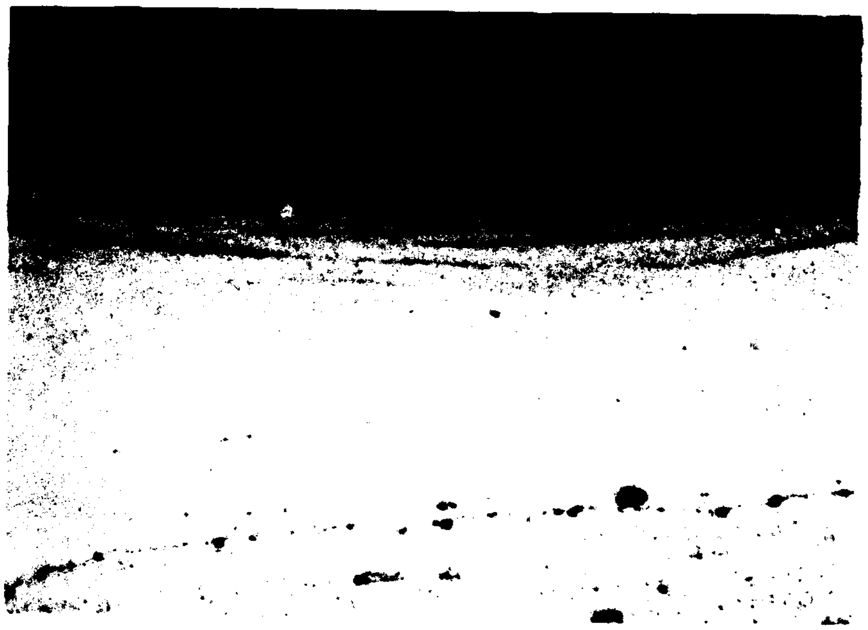
M50

Distance from Surface (in.)	Flojet Knoop (100g)	Flojet HRC (conv)	Flood Knoop (100g)	Flood HRC (conv)
.001	941	69.0	929	68.5
.005	989	70+	945	69.0
.010	960	69.5	952	69.5

* Note: Values at .001 and .005 represent an average of 3 to 6 readings.

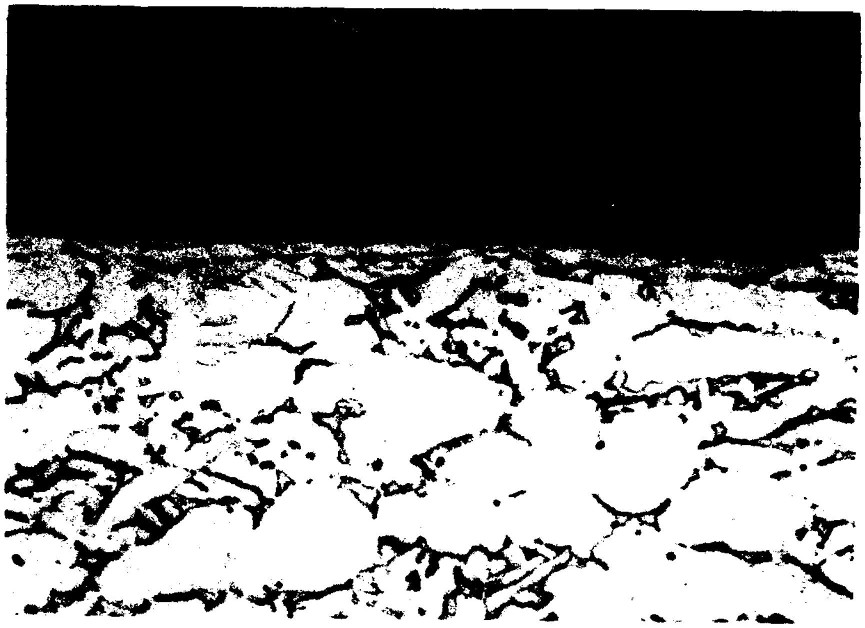


Flojet Test Condition

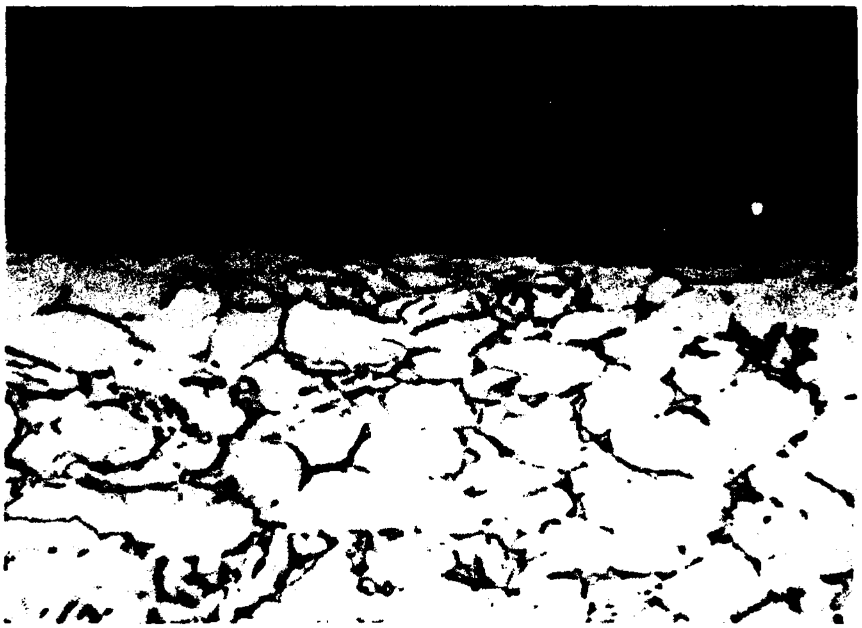


Flood Test Condition

Figure 1 - Typical surface microstructural features of 7075 Al Alloy.
Etchant - HF, HNO_3, H_2O **Mag: 1000X**



Flojet Test Condition



Flood Test Condition

Figure 2 - Typical surface microstructural features of Ti-6Al-4V Alloy.
Etchant - HF, HNO_3, H_2O Mag: 1000X

Flojet Test Condition

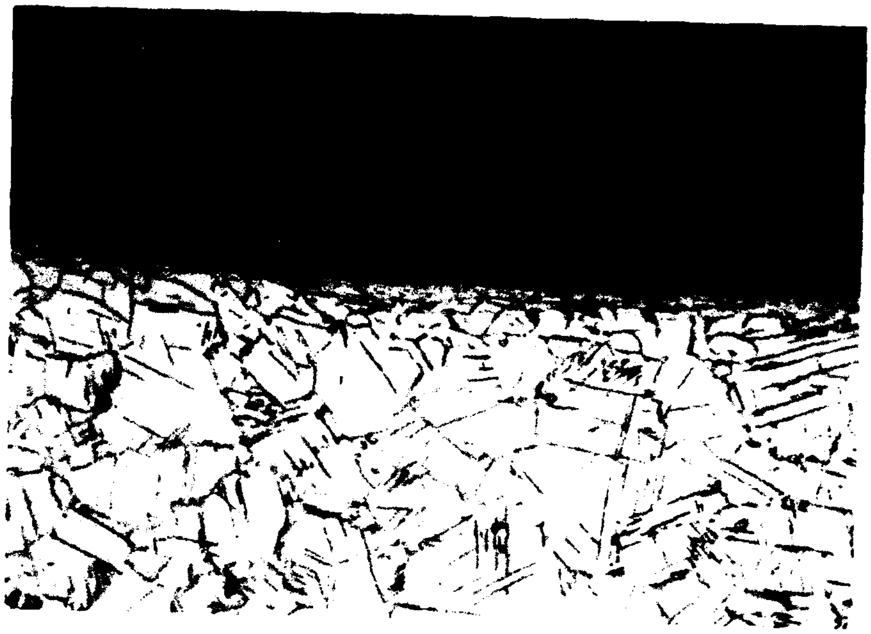
Flood Test Condition

Figure 3 - Typical surface microstructural features of AISI 4340 Steel.
Etchant - Nital, 2% Mag: 1000X

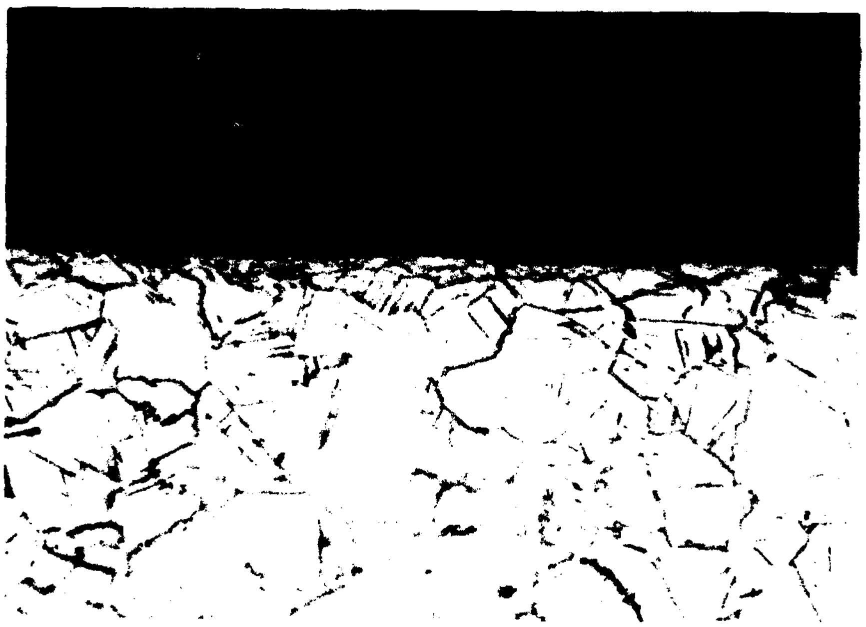
Flojet Test Condition

Flood Test Condition

Figure 4 - Typical surface microstructural features of 17-4 PH Stainless.
Etchant - Kalling's Mag: 1000X



Flojet Test Condition



Flood Test Condition

Figure 5 - Typical surface microstructural features of Inconel.
Etchant - Kalling's Mag: 1000X

Flojet Test Condition

Flood Test Condition

Figure 6 - Typical surface microstructural features of M50.
Etchant - Nital Mag: 1000X